JRS
Interferometry and Vibration Isolation
Scientific Instruments
Fabrik am Weiher
8909 Zwillikon
Switzerland
Tel: +41 1 776 33 66
Fax: +41 1 776 33 65
E-Mail: info@jrs-si.ch

A STABLE, SCANNING OR NON-SCANNING, FABRY-PEROT INTERFEROMETER

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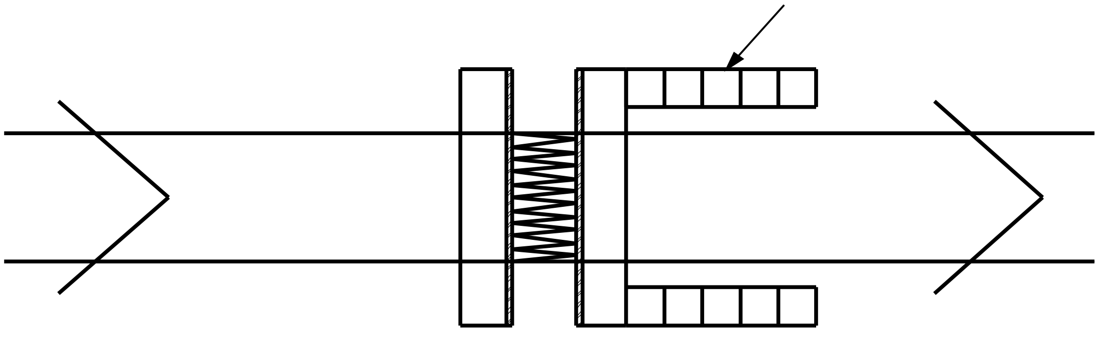
Introduction

The Fabry-Perot is a very high resolution spectrometer commonly used for analysing visible light. As shown in figure 1a it consists of two very flat mirrors arranged accurately parallel to one another with a suitable scanning device (such as a piezoelectric translator) which enables the spacing between the mirrors to be varied.

Figure 1a



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Switzerland
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The device acts as a tuneable resonator. Light incident perpendicularly on the first mirror will be transmitted by the interferometer whenever the wavelength λ satisfies the condition

$$2nL = p\lambda \qquad -1$$

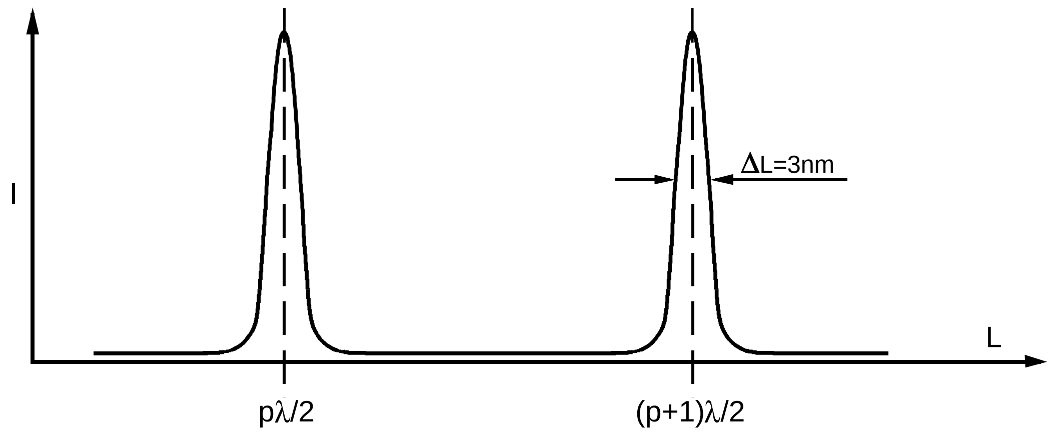
where L is the spacing between the mirrors, n is the refractive index of the medium between the mirrors and p is an integer. In many applications the spacing L is varied by piezoelectric means.

The transmission curve for the interferometer is given by

$$T = 1/\left[1 + \left(4F^2/\pi^2\right)\sin^2\left(nL \cdot 2\pi/\lambda\right)\right] \qquad -2$$

and shown in figure 1b

Figure 1b



Because the light makes many reflections between the mirrors the resonant peaks are sharp. The ratio of peak spacing to peak width is known as the finesse F. The finesse depends on mirror flatness and reflectivity and in typical applications values of finesse of around 30 - 100 are used.

Stability of Fabry-Perot

Although the Fabry-perot is a very useful instrument in view of its very high resolution, it is a highly sensitive device which is difficult to keep stable. Referring to figure 1b it is seen that a change in mirror spacing of only 3nm is needed to scan through the transmission peak. For stable operation therefore both mirror spacing and parallelness must be maintained to an accuracy of the order of 1nm.

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In practice such a high stability is very difficult to achieve. Even using low expansion materials for the construction, purely passive stability would require maintaining a temperature stability of better than 0.1C and even then mechanical relaxation tends to limit the performance.

Although active feedback stabilisation is often used in practice, this can only be used in a scanning mode and normally requires a reference beam. The feedback system works by modulating the mirror spacing and alignment in order to maximise the height of the transmitted reference beam. Such systems are complex and cannot be used to stabilise a non-scanning interferometer.

A scheme using white light fringes has been used for maintaining parallelism even in a non-scanning interferometer but the scheme cannot be used for maintaining mirror spacing.

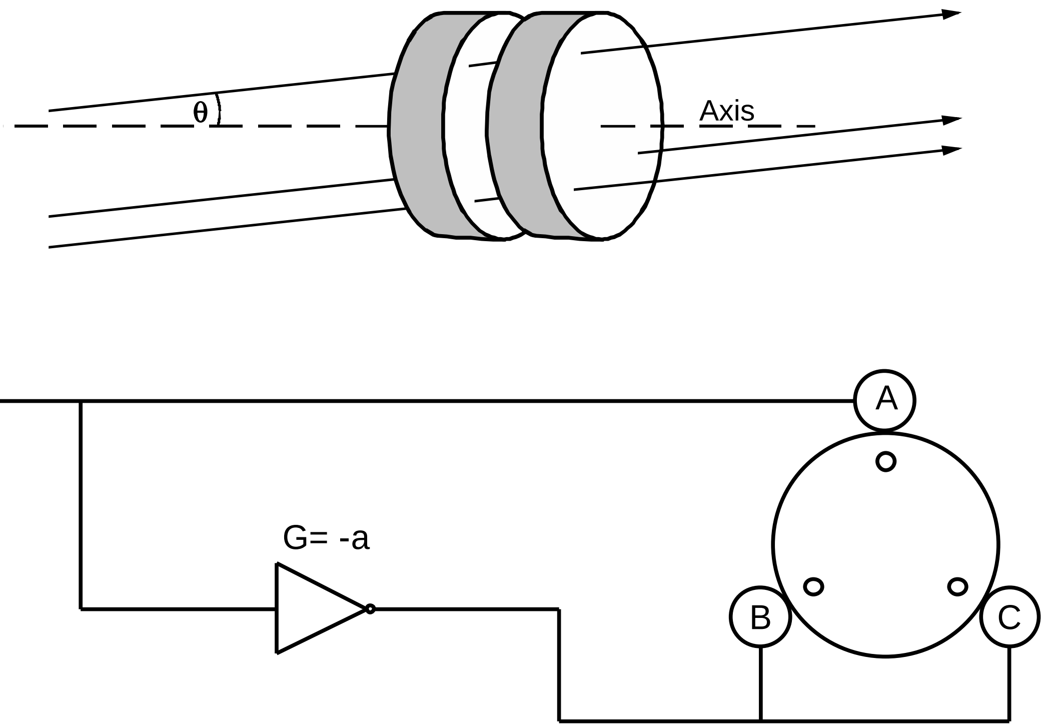
A Novel device

A method is described below which in a simple manner allows complete long-term stability of a Fabry-Perot to be achieved. The method applies equally to a scanning or non-scanning interferometer.

Description

The method proposed here uses three parallel reference beams. The beams are passed not perpendicularly, but at a small angle θ through the interferometer. Sensors measure the intensity of the beams and feedback loops optimise the intensity of each beam. This is indicated schematically in figure 2.

Figure 2



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For the reference beams:

$$2nL \cdot cos\,\theta = p\lambda \qquad -3$$

The feedback loops maintain this condition, and so as θ is varied the mirror spacing L will be changed accordingly. Typical values for the angle θ lie between 0 and about 3degrees. As an example, if L is equal to 3mm and λ equal to 0.5µm, the spacing L will be changed by λ/2 as θ is varied from 0.01rdn to about 0.0163rdn (roughly 0.573° to 0.936°).

The sensitivity of the spacing L to changes in θ can be obtained by differentiating equation 3:

$$\frac{\delta L}{L} = \frac{-\delta n}{n} + \delta\theta \cdot tan\,\theta + \frac{\delta\lambda}{\lambda} \qquad -4$$

If δL is equal to 1nm for a spacing L of 3mm and θ is 0.01rdn, then δθ is 3.3×10^{-5}rdn.
This calculation immediately shows the advantage of this scheme. A rotation of 3.3×10^{-5}rdn is easy to produce accurately and reproducibly – it corresponds for example to a movement of about 10µm at the end of a lever 330mm long.

It should be noted that a rotation is basically temperature invariant – a uniform temperature change will alter the dimensions but not angles (provided of course that the materials used have the same coefficient of thermal expansion).

Equation 3 shows that the mirror spacing depends not only on cosθ but also on the laser wavelength λ and the refractive index n of the medium. The variation of n is unimportant as will be shown below. The wavelength of a reference single frequency laser can be better than 1 part in 10^8. Applied to the above example this could lead to a variation in mirror spacing of just 3.10^{-2}nm which is negligible.

Stabilising spacing and parallelness

Three piezoelectric translators are used for changing the mirror spacing and adjusting the parallelness. This is indicated in figure 2. In order to make the stabilisation of the three beams independent of one another it is convenient to drive the transducers with mixed signals. For example if translator A receives the signal $V_A - a(V_B + V_C)$, and similar for the other axes, the small term "a" can be adjusted so that the signal V_A only affects the mirror spacing for beam A. Likewise for beams B and C.

By adding a modulation signal to the signals $V_{A,}$ etc. standard phase sensitive detection techniques can be used to optimise the intensity of each beam.

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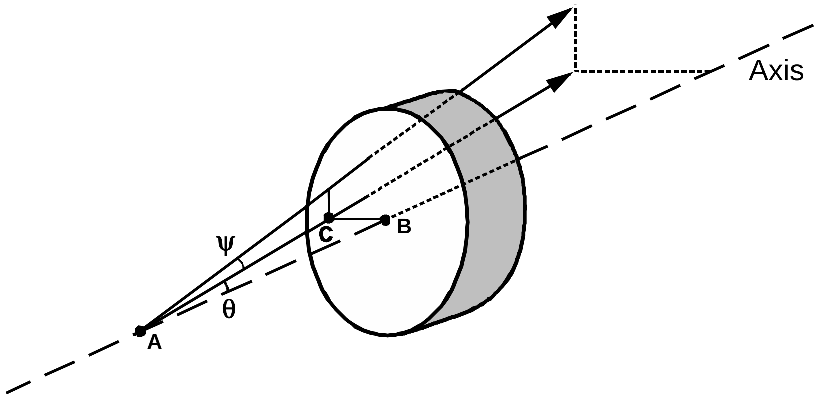
Stabilisation without modulation signal

A modulation signal inevitably adds some noise to the system. A technique described below enables stabilisation to be achieved without using a modulation signal.

In figure 3 just one of the three stabilisation beams has been shown for clarity. As in the scheme of figure 2 this beam is rotated by external means through the angle θ in the plane ABC. Now however a second beam has been formed which is at a small angle ψ to this plane. The angle ψ is of the order of 0.5 to 1 degree.

Figure3



For the first beam the equation 3 holds, namely

$$2nL_0 \cdot cos\,\theta = p\lambda$$

while for the second beam

$$2nL_\psi \cdot cos\,\theta \cdot cos\,\psi = p\lambda$$

Since $cos\theta$ is very close to unity, these equations show that L_0 - L_ψ is essentially independent of the scan angle θ. If the mirror spacing L is set midway between L_0 and L_ψ the intensities of both beams will be the same.

By measuring the difference in the intensities it is now possible to determine the sign of the error ΔL in L. Referring to figure 4 it is seen that if the error in L is negative (L too small) then the intensity I_0 is greater than I_ψ, while for positive ΔL the opposite is true.

If the difference in the intensities is amplified and used to drive the translator, both signals will be optimised until the intensity difference is zero corresponding to the situation c in figure 4.

This stabilisation method can of course be applied to all axes simultaneously. No modulation signal is required resulting in less noise and better stability.

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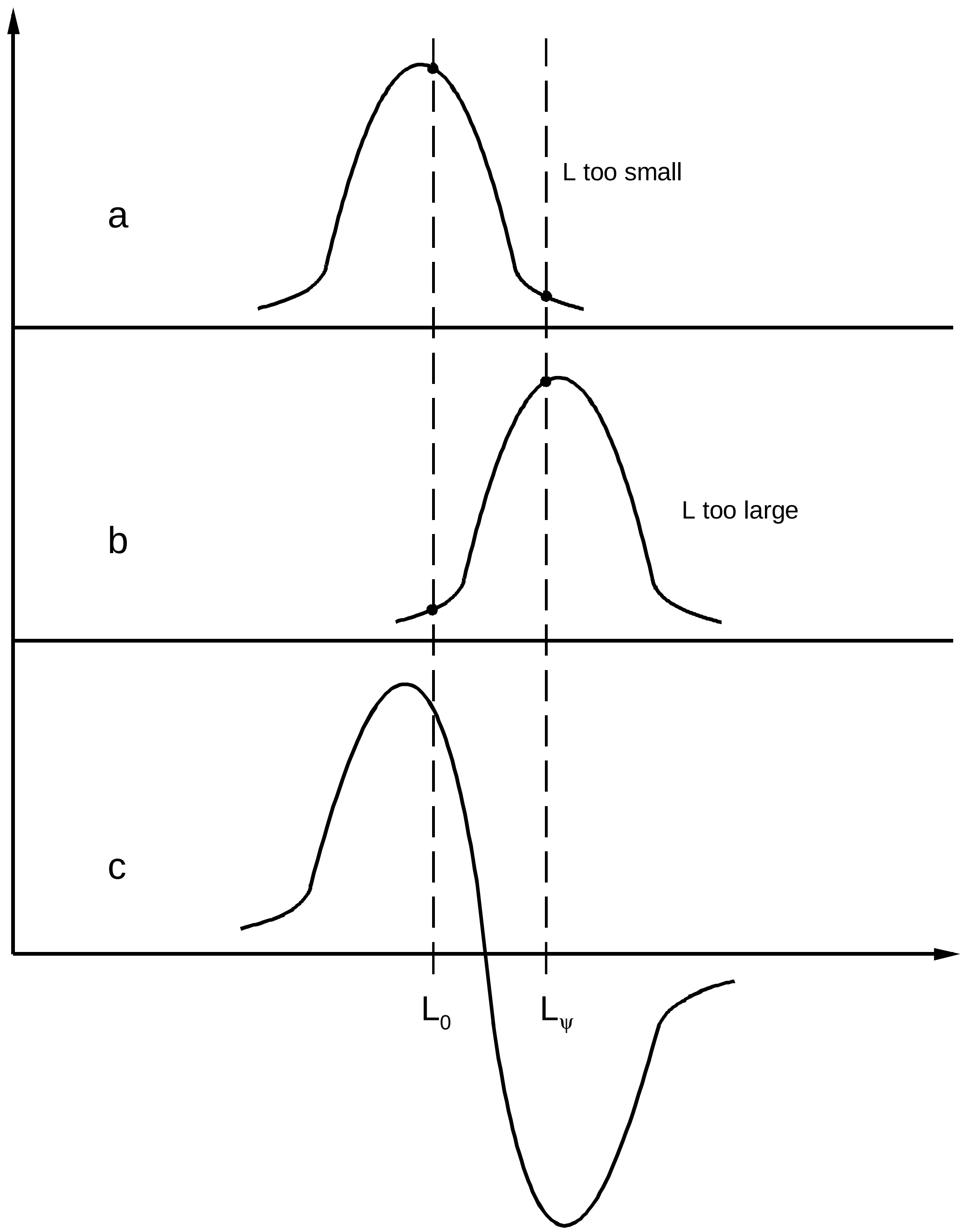
Figure 4



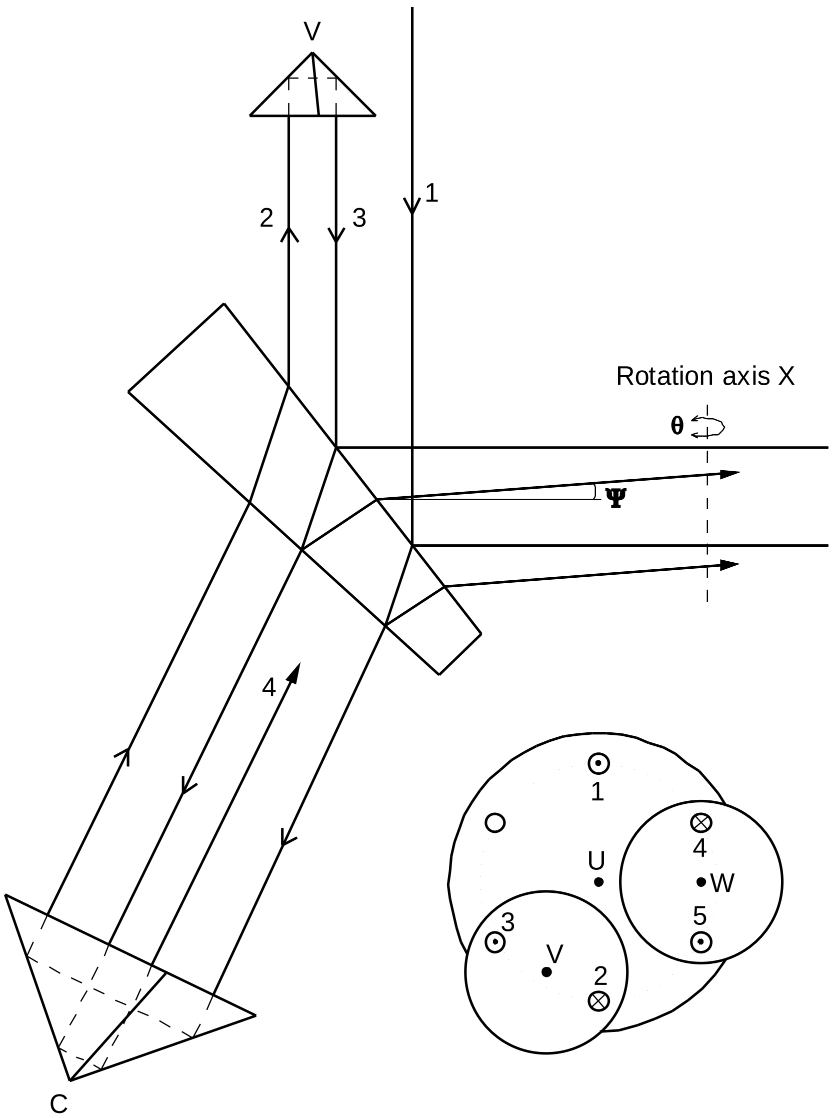
Practical means of deriving the reference and stabilisation beams

The interferometer as described above requires 3 reference beams and 3 stabilisation beams. The reference beams must be accurately parallel to each other, as must the stabilisation beams. The angle ψ between reference and stabilisation beams must remain constant as the angle θ is varied. Figure 5 shows a simple scheme by which the beams can be derived.

Three corner cubes U, V, W and a small angle wedge A are employed. The relative positions of the 3 corner cubes are shown in the insert. The incident laser beam 1 strikes the wedge at an angle and is refracted through the wedge and reflected from both of its surfaces. The reference beam is formed by reflection from the front side of the uncoated wedge, the stabilisation beam by reflection from the rear surface. After transmission through the wedge the beam is reflected successively by corner cubes U and V leading to the beam 3 which then forms the second pair of reference and stabilisation beams. The transmitted beam after reflection from corner cubes U and W becomes beam 5 which forms a third pair of reference and stabilisation beams. (This third pair and corner cube W are not shown for clarity).

The 3 pairs of beams then fall on a mirror which can be rotated about the axis X, thus allowing the angle θ to be varied while maintaining a constant angle ψ .

Figure 5



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Changing the mirror spacing

The interferometer is scanned by varying the angle θ. Standard mechanical and optical techniques can be used to vary this angle. It is clear that the mirror spacing L does not vary linearly with angle θ, but rather via the cosine function. By varying θ under, for example, stepper motor control it is straightforward to use computer control to linearise the scan.

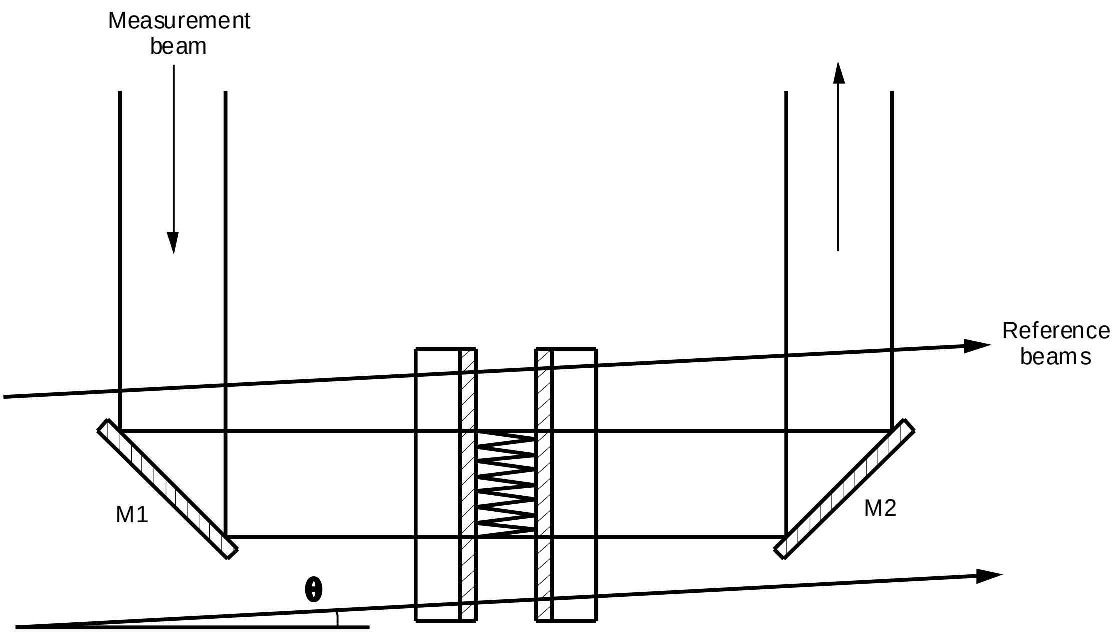
Practical use

The discussion so far has described how to stabilise and scan the interferometer using an angularly displaced reference beam. In practice the interferometer will be used to scan and analyse some light source. It is important that the reference beam does not affect the measurement. Two methods of achieving this aim are described below:

1 Space sharing

The three reference beams occupy a relatively small part around the edge of the interferometer mirrors. The remaining area of the mirror surfaces can be used for measurements. Figure 6 shows how this might be realised. Two mirrors M1 and M2 (smaller than the interferometer mirrors) are used to steer the measurement beam in and out of the interferometer. The reference beams pass outside M1 and M2. It is assumed here, although it is not a condition, that the measurement and reference beams have similar wavelengths.

Figure 6



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Switzerland
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Fax: +41 1 776 33 65
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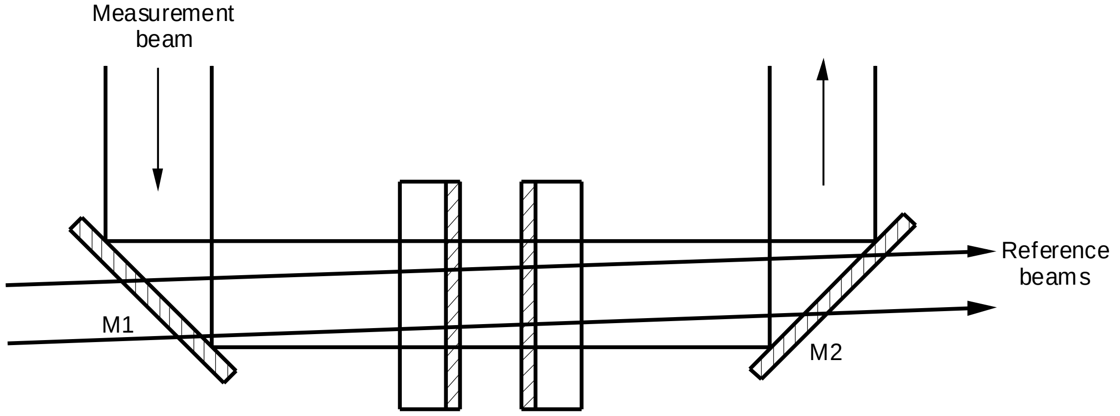
2 Separate Wavelengths

An alternative scheme where the measurement and reference beams have widely differing wavelengths uses dichroic mirrors as shown in figure 7. This is essentially the same arrangement as in figure 6 except that now the whole of the interferometer mirror area is available for measurement. The interferometer mirrors in this case must be coated for high reflectivity at both reference and measurement wavelengths.

Figure 7



Dichroic mirrors M1 and M2 transmit reference wavelength, reflect measurement wavelength.

Effect of refractive index of medium

When using the interferometer for a measurement a wavelength λ_1 will be measured in order q, following equation 1, where

$$2nL = q\lambda_1$$

Comparing this with equation 3 shows that

$$\lambda_1 = \frac{\lambda p}{q \cdot \cos\theta}$$

In other words the measured wavelength does not depend on the refractive index (except through dispersion in n if λ_1 and λ are widely differing).

Conclusion

The method described above allows the construction of a highly stable Fabry-Perot interferometer in which the transmitted wavelength is preset via a micrometer screw under computer control. It is therefore an absolute instrument in the same way that a grating spectrometer is absolute.

It does not require repetitive scanning in order to stay stable and can transmit continuously a fixed predetermined wavelength, or scan a range of wavelengths as required.
Because it is absolute the scanned wavelength is always under direct control and so it is straightforward to combine two or more such instruments in a tandem combination in order to increase the free spectral range.