1996BASI...24..849D

Bull. Astr. Soc. India (1996) **24,** 849–854

Some recent advances in astronomical Fabry-Perot spectroscopy

J.N. Desai

Physical Research Laboratory, Ahmedabad 380 009, India

Abstract. The Purpose of the present article is to provide a broad perspective of applications of Fabry-Perot Spectroscopy to astronomy, especially focussing attention on some known aspects which are assuming greater importance. Basic details of the Fabry-Perot device are omitted, for which appropriate references are given.

1. History

Fabry-Perot spectroscopy was invented by Fabry and Perot (1897) and the technique specifically made use of a property of multiple beam interference first noted by Airy (1833). For a look into the early history and evolution of the method interested readers may consult the monograph by Vaughan (1989). In the context of its applications to astronomy, it was first used to observe solar photospheric absorption lines (Fabry and Perot, 1902) and then emission lines in Orion Nebula (Fabry and Buisson 1911). Another notable use was for solar coronal spectroscopy on the green line by Jarret and Kluber (1955) during a total solar eclipse.

Luminosity advantage of Fabry-Perot (and similar interferometric spectrometers) over the grating and prism devices, was first pointed out by Jacquinot (1954). Chabbal (1953) studied the optimization conditions involved in the practical use of Fabry-Perot spectrometers. Over the past three decades, the Fabry Perot spectroscopy is being increasingly used both in astronomy as well as in atmospheric optics. A major factor contributing to the successful application of Fabry-Perot spectroscopic techniques to a variety of problems involving faint sources has been the development of almost zero absorption multilayer high reflection dielectric coatings; which enables realization of high finesse without significant loss of luminosity. This can be seen by examining the Airy formula for the transmission of a FP etalon as a function of wavelength λ, angle of incidence θ and the optical gap μt between the etalon plates; viz.

$$I_{\lambda,\theta} = \frac{T^2}{(1-R)^2} \; \frac{1}{1 + \frac{4R}{(1-R)^2} \mathrm{Sin}\, \phi^2}$$

© Astronomical Society of India • Provided by the NASA Astrophysics Data System

with R+T+A = 1; where R, T and A are respectively the reflection, transmission and absorption coefficients of the etalon surface and $\phi = \frac{2\pi\mu t}{\lambda}$

$$I_{\lambda\theta} = \left[1 - \left[\frac{A}{1 - r}\right]\right]^2 \frac{1}{1 + \frac{4R}{(1 - R)^2}} \mathrm{Sin}^2 \phi;$$

which shows that the peak value of $I_{\lambda\theta}$ can reach a sharp maximum ≈ 1; provided A ≈ 0 as $R \to 1$. On the other hand, at high reflectivity the peak transmission can be drastically reduced even by small contribution from A.

As the aim of the present article is essentially to focus attention on some recent developments in Fabry-Perot techniques, the basics of FP Spectroscopy are largely omitted. Interested readers may refer to the readily available literature for this [cf. Meaburn 1970, 1976; Atherton, 1989: Desai, 1984]. One would like however, to stress here that efficient use of FP Spectroscopy requires that proper attention be paid to the parallelism, reflectivity, selection of the free spectral range and the aperture width. It is also necessary to pay proper attention to the deconvolution procedure adopted to recover the object spectral profile from the observed profile. For details on these aspects one may refer Chabbal (1953); Vaughan (1989), Hernandez (1966, 1978, 1979, 1986).

2. Fabry-Perot as an imaging spectrometer

Classically, F.P. interferogram of an extended object is taken in a spectral line by (i) collimating the flux (prefiltered with a suitable interference filter) focussed in the image plane by the telescope objective, (ii) passing the collimated beam through a Fabry-Perot etalon and (iii) reimaging the object together with FP fringes in the camera focal plane (Meaburn 1976, pp.168; Debi Prasad *et al.*, 1988). Although such interferograms can be very useful in mapping parameters like velocity fields and temperatures over the object, the interpretation of fringe profiles can be rendered complicated by the presence of strong intensity gradients over the object field.

To circumvent the problem posed by the intensity gradients over the object, in proper interpretation of the fringe profiles, Courtes (1967) developed the technique of taking "insect eye interferograms". Here, the FP etalon is used in what is called telecentric mode; i.e. it is placed in the focal plane of the telescope at a rather large F ratio; and discrete interferograms are formed by an array of microlenses, each interferograms sampling a discrete spatial element of the object field. Intensity variations over each spatial element sampled by a microlens do not affect the fringe profile, which then carries velocity information averaged over the element. Obviously, there is a large sacrifice of the spatial resolution. For details one may consult Meaburn (1976; pp.175-180).

© Astronomical Society of India • Provided by the NASA Astrophysics Data System

1996BASI...24..849D

Use of modern 2 dimensional detectors like CCD together with piezoelectrically scanned servo controlled FP etalons in which etalon gap can be quickly stepped without loss of parallelism, permits one to use FP as an imaging spectrometer with almost seeing limited spatial resolution. Several of such systems are now in use at telescopes (Atherton *et al.* 1982; Joncas & Roy 1984; Jockers 1986; Seema *et al.* 1995). In these systems, a "file" of interferograms is recorded with the etalon sequentially tuned with suitable number of steps ($\approx$ Finesse) to cover one complete free spectral range. Line profile information being recorded on discrete pixels individually, the intensity gradients over object field do not pose a problem.

With rapid developments in infrared array detectors, both for mid and near infrared, the Fabry-Perot is becoming a suitable choice for imaging astronomical objects like star forming regions in desired emission lines. One of the important applications has been the study of velocity fields in the shocked H_2 regions (Sugai *et al.* 1994; Tanaka *et al.* 1994; Watarai *et al.* 1994).

3. Solid etalons

Thin wafers of suitable optical materials can be figured sufficiently plane parallel to be used as high quality etalons with finesse values as high as ~ 30 (Finesse coefficient of a Fabry-Perot etalon measures the number of resolved spectral elements that can be accommodated without overlap of adjacent interference order). Such devices are being commercially manufactured out of i) fused silica; ii) Mica and iii) Lithium Niobiate.

Solid etalons have some special advantages over airgap etalons. The refractive index μ of the etalon material being higher, the field of view Ω given by $\frac{2\pi\mu^2}{R}$ is greater for a given resolving power R; resulting in more flux collection from extended objects. Secondly, their stability is very good, provided proper temperature control is used. Further, the absence of other interfaces means total freedom from ghost fringes; making the solid etalons very convenient for taking interferograms. On the disadvantage side, their etalon gap cannot be changed; and the tunability is highly limited (except in the case of Lithium Niobiate which can be tuned by applying voltage).

Fused Silica and Mica etalons can be tuned only with temperature change; and over a very limited range. For fused Silica, the tuning coefficient is $\frac{\delta\lambda}{\lambda} \approx -6.6 \times 10^{-6}/^{\circ}\mathrm{C}$; mainly due to the refractive index change, thermal expansion contribution being an order of magnitude less. Mica etalons have a coefficient $\frac{\delta\lambda}{\lambda} \approx +0.062$ Å/$^{\circ}$C. Neither of the two can be temperature tuned over full free spectral range which could typically be ≈ 5 Å.

Etalons made of mica have an interesting property that they show transmission wavelengths at two slightly different wavelengths depending upon the polarization (linear) direction of the incident light and the etalon thickness. This is due to the birefrigent property of mica having refractive indices $\mu_e = 1.596$ and $\mu_e = 1.591$. This property has been explored

1996BASI...24..849D

by Smartt (1982) for discriminating emission lines against continuum. Solid etalons as narrow band filters have been compared with birefringent filters (Austin, 1972).

Lithium Niobiate is an electro-optical crystal and hence, solid etalons made from this material (manufactured by CSIRO, Australia) can be wavelength tuned by applying voltage. Etalons fabricated with the plate surface perpendicular to the optical symmetry axis (z cut) can be tuned to 0.4 Å/1000 V; and show transmission peak independent of the polarization state.

F.P. etalons made from Lithium Niobioate with Y cut; that is, with the optical symmetry axis parallel to the plate surface would show transmission characteristics which are dependent on the state of linear of polarization of the incident light. Bonaccini nd Smartt (1988) have considered application of such etalons to detect solar cornal emission, through their capacity to subtract continuum at an adjacent wavelength. With such an etalon of 0.1 mm thickness, at 5302.9 Å (corresponding to the green coronal line); wavelength tuning is $\approx$ 1 Å/1000 V for ordinary ray; whereas the wavelength of transmission is almost independent of applied voltage for the extra-ordinary ray; thus offering a very convenient means of sky chopping to reject the background. Desai *et al.* (1979) have used a different scheme for rejecting condinuum, by employing suitable masks in the focal plane where fringes are formed. This scheme has been used very successfully for detecting daytime emission of 6300 Å (01) airglow (Narayanan e*t al.* 1989; Sridharan *et al.* 1992). However, its use on astronomical objects involves a modification using telecentric optics, which involves a modification using telectric optics, which although suggested (Debi prasad e*t al.* 1988), has not been tried out yet.

4. Multiple Fabry-Perots and Fabry-Perot in tandem with birefringent filters

One of the serious drawbacks of a Fabry-Perot etalon as a spectrometer is its very limited free spectral range $\Delta\lambda$ given by $\frac{\lambda^2}{2\mu t}$. With the overall finesse factor N at best $\simeq$ 30; which is also number of resolved spectral elements of width $\delta\lambda$ that can be accommodated within the available free spectral range (i.e. wavelength range without order overlapp). Further, the nonzero transmission at the fringe minima implied by the Airy function poses problems when profiles are observed against strong continuum.

Tandems of Fabry-Perot have been used to overcome these problems. One of the sophisticated early designs has been that of a combination of triple etalons called PEPSIOS, with vernier spacer ratios specifically designed to suppress transmission at other orders (Mack *et al.* 1963). For more details on the uses and characteristics of multiple etalon systems reader is recommended to refer Vaughan (1989 pp. 216-253).

However, in order to take full advantage of recent developments in imaging detectors like CCDs; in using Fabry-Perots as imaging spectrometers (for absorption lines and in presence of considerable continuum), combinations of birefringent filters with Fabry-Perot seem promising. The concept uses the wider field advantage of birefringent filters, using them at lower resolution and scanning the line of interest at high resolution using a Fabry-Perot. Two versions of such spectrometers have been reported for imaging studies on the Sun. The one

© Astronomical Society of India • Provided by the NASA Astrophysics Data System

reported by Bendlin *et al.* (1992) uses a universal birefringent filter of pass band ≃ 0.5 Å; scanning the line under observation at a resolution of ≃ 30 mÅ with a Fabry-Perot. In a more sophisticated instrument designed by Bonaccini *et al.* (1989) (see also Bonaccini and Staufer, 1990) the line is scanned by both universal birefringent filter and Fabry-Perot synchronously.

5. Summary

Fabry-Perot Spectroscopy offers a very efficient and convenient method for high resolution line profile studies both in emission as well as in absorption. However, in correctly recovering the source line profile, due attention must be paid to deconvolve the observed profile with carefully determined Fabry-Perot instrument profile.

The problems posed by nonzero transmission at the fringe minima, and rather narrow free spectral range between successive transmission orders, can be taken care of by suitable tandem designs. Recent advances both in Fabry-Perot fabrication and control techniques; as well as in imaging electronic detectors, make use of Fabry-Perot methods more attractive for high resolution line profile studies.

Acknowledgement

Author acknowledges the financial assistance from Dept. of Space, Government of India.

References

Airy G.B., 1833, Phil. Mag., 2, 20.

Atherton P.D., Taylor K., Pike C.D., Farmer C.F.W., Parket N.M., Hook R.N., 1982, MNRAS, 201, 661.

Atherton P.D., 1988, in Instrumentation For Ground Based Optical Astronomy, Ed. Robinson L.B., Springer Verlag, p. 124.

Austin R.R., 1972, Instrum. in Astronomy, SPIE. 28, 141.

Bendlin C., Volkmer R., Kneer F., 1992. A & A, 257, 817.

Bonaccini D., Smartt R.N., 1988, Appl. Opt. 27, 5095.

Bonaccini D., Cavallini F., Ceppatelli G., Raghini A., 1989, A & A, 217, 368.

Bonaccini D., Staufer F., 1990, A & A, 229, 272.

Chabbal R., 1953, J. Rech. CNRS, 24, 138.

(English translation R.B. Jacobi from AERE, Harwell, U.K. Lib. Transl. 778).

Courtes G., Georgelin Y., 1967, J. Physique, 28C-2, 218.

Debi Prasad C., Desai J.N., Chandrasekhar T., Ashok N.M., 1987, in Opto Electronic Imaging, Ed. Juyal D.P., Mehta P.C. and Sharma M.K., Tata McGrawHill (New Delhi) p. 101.

Debi Prasad C., Chandrasekhar T., Desai J.N., Ashok N.M., Sivaraman K.R., Rajmohan R., 1988, PASP, 100, 702.

Desai J.N., 1984, Proc. Ind. Sci. Acad. 93, 189.

Desai J.N., Anandrao B.G., Raghavarao R., 1979, Appld. Opt. 18, 420.

Fabry Ch., Perot A., 1897, Ann. Chim. Phys. 12, 459.

Fabry Ch., Perot A., 1902, Ann. Chim. Phys. 25, 261.

Fabry Ch., Buisson H., 1911, ApJ. 33, 406.

Hays P.B., Kileen T.L., Kennedy B.C., 1981, Space Sci. Instrum. 5, 395.

Hernandez G., 1966, Appld. Opt. 5, 1745.

Hernandez G., 1978, Appld. Opt. 17, 2967.

Hernandez G., 1979, Appld. Opt. 18, 3826.

Hernandez G., 1986, Fabry-Perot Interfermeters', Camb.univ.press.

Jacquinot P., 1954, J.O.S.A., 44, 761.

Jarret A.H., Von Kluber H., 1955, MNRAS, 115, 343.

Jockers K., 1986, ESO Messenger 44, 12.

Joncas G., Roy J., 1984, PASP, 96, 263.

Killeen T.L., Kennedy B.C., Hays P.B., Syamanow D.A., Ceckowski D.H., 1983, Appld. Opt. 22, 3503.

Mack J.E., Mc Nutt D.P., Roessler F.L., Chabbal R., 1963, Appld. Opt. 2, 873.

Meaburn J., 1970, Astr. Sp. Sci. 9, 206.

Meaburn J., 1976, "Detection and Spectrometry of Faint Light", D. Riedel , Dordrecht.

Narayanan R., Desai J.N., Modi N.K., Raghavarao R., Sridharan R., 1989, Appld. Opt. 28, 11.

Seema P., Anandarao B.G., Banerjee D.P.K., Jog N.S., Patel R.T., 1992, PASP, 104, 1091.

Smartt R.N., 1982, Instrum. in Astron. IV, SPIE, 331, 442.

Sridharan R., Haider S.A., Gurubaran S., Sekar R., Narayanan R., 1992, J.G.R. 97, 13715.

Sugui H., Usuda T., Kawabata H., Inove M.Y., Kataza H., Tanaka M., 1994, in Infrared Astronomy with Arrays, Next Generation, Ed. Ian S. McLean, Kluwer Acad. Publ., 527.

Tanaka M., Usuda T., Kawabata H., Sugui H., Inove M., Kataza H., in Infrared Astronomy with Arrays, Next Generation, Ed. Ian S. McLean, Kluwer Acad Publ., 529.

Vaughan J.M., 1989, The Fabry Perot Interferometer, History, Theory Practice and Applications, Adam Hilger Publ.

Watarai H., Chaen K., Matsuhara H., Matsumoto T., Takahashi H., 1994, in Infrared Astronomy with Arrays - Next Generation, Kluwer, 339.

© Astronomical Society of India • Provided by the NASA Astrophysics Data System