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To cite this version:

J. James, R. Sternberg. AN APPLICATION OF THE FOCAL ISOLATION PRINCIPLE TO A NEW TYPE OF OPTICAL SPECTROMETER. Journal de Physique Colloques, 1967, 28 (C2), pp.C2-326-C2-329. <10.1051/jphyscol:1967262>. <jpa-00213246>

HAL Id: jpa-00213246
https://hal.archives-ouvertes.fr/jpa-00213246

Submitted on 1 Jan 1967

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AN APPLICATION OF THE FOCAL ISOLATION PRINCIPLE TO
A NEW TYPE OF OPTICAL SPECTROMETER

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Abstract. — A design study is made of a spectrometer which uses a lens with chromatic aberration as the focusing element. A grid of equally spaced opaque and transparent strips is imaged on to a similar grid so that only one wavelength is in focus. If one of the grids is made to oscillate in a direction perpendicular to the bars, this particular wavelength is amplitude modulated and can be detected by a synchronous detection system. Other wavelengths which give images of lower contrast then give a smaller amplitude of modulation. Calculations show that a resolution of 1 Å is possible and that the étendue is limited only by the geometrical aberrations and can be made very large.

Résumé. — Etude d'un spectromètre qui utilise une lentille douée d'aberration chromatique comme élément focalisateur. L'image d'une grille à intervalles pleins et vides égaux est projetée sur une grille identique de telle sorte que la focalisation est correcte pour une seule longueur d'onde. Si l'une des grilles oscille perpendiculairement à la direction des traits, cette longueur d'onde est modulée en amplitude et peut être détectée par une démodulation synchrone ; les autres longueurs d'onde qui donnent des images de contraste plus faible donnent une modulation d'amplitude moindre. Les calculs montrent qu'une résolution de 1 Å est possible et que l'étendue est limitée seulement par les aberrations géométriques et peut être très élevée.

1. Introduction. — The «efficiency» of a spectrometer has been defined by Jacquinot [1] as the product of the resolving power $R$ and the étendue, $L$. The same author showed that systems such as the Fabry-Perot spectrometer and the Michelson Multiplex Spectrometer, which disperse the radiation in two dimensions, have efficiencies which are very large compared to those of normal grating spectrometers. In these high-efficiency devices, the efficiency is strictly limited and defined by geometry to $2\pi$ steradians per unit aperture. In grating spectrometers the efficiency, although smaller, is not limited in this way. The dispersion is in only one direction, perpendicular to the optic axis, and it is possible in principle, although not in practice, to increase the étendue to as large a value as we please, by using longer and longer slits. The maximum efficiency that can be obtained in this way is still very much lower than that obtainable from a Fabry-Perot spectrometer.

There is still one further dimension available for increasing the efficiency. If the dispersion is in the direction of the optic axis, the two remaining directions, both perpendicular to the optic axis, are free to be used to increase the étendue. The same sort of limit will apply to this system as to a grating spectrometer slit length, but still it should prove possible to realise an efficiency much greater than that even of a Fabry-Perot spectrometer.

2. The Focal-Isolation Principle. — A possible way of achieving dispersion along the optic axis is to use a focal-isolation spectrometer. Focal isolation spectrometers were first described by Rubens and Wood [2] in 1911, when the principle was used to isolate far infra-red radiation for the first time. The chromatic aberration of a lens is used to form an image of a pinhole at only one wavelength on an exit pinhole. Other wavelengths are rejected because their extra-focal images are intercepted by the screen (Fig. 1).

Such a device is necessarily of low resolution and very low étendue and is not used if any other way can be found.
However, there is no reason why the device should be restricted to one on-axis-pinhole and its conjugate point. One may imagine a screen $S_1$ with any number of pinholes, and a conjugate screen $S_2$ with pinholes at all points conjugate to the pinholes in $S_1$. Provided that the aberrations are small enough, a large increase in étendue is, in principle, possible. If this process is taken to its logical conclusion, the screen $S_1$ is replaced by a fine screen grid (Fig. 2) consisting of equal opaque and transparent strips, each of width $a$. An exactly similar grid at $S_2$ will then allow all the radiation at the in-focus wavelength to pass, and if is moved sideways a distance $a$ it will prevent all the radiation at the in-focus wavelength from passing.

3. **The focussing of a fine line screen by a lens.**

The extra-focal image of a fine line screen that is formed by a lens has been described by Hopkins [3], who defines a « response function » $D$ which represents the contrast to be expected in the image of a line grid. It is assumed that the optical system is perfectly corrected, and that the only defect is that of focus. The contrast $D$ is a function of two variables, in particular of (Hopkin's notation)

$$S = 2 F \lambda R$$

and

$$\omega = \frac{\Delta f}{8 F^2}$$

where

$\lambda$ = wavelength of light,
$F$ = focal ratio of lens,
$R$ = no. of line pairs per centimeter,
$\Delta f$ = distance of the image screen $S_2$ from the focussed image of $S_1$.

The quantity $\omega$ is the deviation from the reference sphere of the wavefront at the edge of the lens aperture. From Hopkin's formulae it is possible to draw a typical curve of contrast $D$, against focus defect $\Delta f$.

Such a curve is shown in figure 3. When the screen grid is very fine so that the image is limited by diffraction effects the curve has in fact the familiar form of $\sin X/X$.

![Fig. 2](image)

![Fig. 3](image)

Using these formulae, plus the usual lens formulae it is possible to derive equations for the resolution and the efficiency of a simple form of isolation spectrometer. The usual criterion for resolution is applied: two wavelengths are resolved when the contrast from one of them is zero at the same screen position that gives a maximum contrast for the other. Efficiency is derived from the usual spectrometer slit criterion—the field diameter shall be 1/50 th of the lens-screen distance.

The resolution and efficiency equations are then:

$$\Delta \lambda = \frac{1.2 (\mu - 1) F}{f (\partial \mu / \partial \lambda) R}$$

$$E = \frac{\lambda (\partial \mu / \partial \lambda) R d^3 \pi}{(\mu - 1) \times 1.2 \times 10^4}$$

where

$\lambda$ = wavelength,
$\partial \mu / \partial \lambda$ = dispersion,
$R$ = lines per centimeter on the screen,
$f$ = focal length.

With

$\lambda = 5 \times 10^{-5}$ cm,
$\partial \mu / \partial \lambda = 2 \times 10^3$ cm$^{-1}$,
$R = 200$ cm$^{-1}$,
$d = 20$ cm,
$f = 100$ cm,
we find
\[ \Delta \lambda = 7.5 \, \text{Å}, \]
\[ E = 84 \, \text{cm}^2 \, \text{steradians}. \]

In this example, values have been chosen which are not extreme, and it may well be found that a much finer line grid than 200 lines per centimeter can be used, and that a glass with higher dispersion than \( 2 \times 10^3 \, \text{cm}^{-1} \) can be found. It is not unreasonable to expect that a resolution of 1 Å can be achieved with a simple system like the one described here. The variations in performance with line spacing and with F-ratio is illustrated in figure 4.

One simple practical realization of the system is shown in figure 5. A single lens is used with a plane mirror behind it to insure that the magnification is always exactly — 1. The geometrical aberrations are:

a) Spherical aberration : corrected by figuring the lens.
b) Coma : primary coma is absent since the system is symmetrical.
c) Astigmatism : only the sagittal focus is used, the grids being radial lines diverging from the optic axis.
d) Field curvature : corrected by using field-flattening lenses near the focal plane to flatten the sagittal field.

An optical system for such an instrument is, at the time of writing, under construction by Messrs. Hilger & Watts, and a trial instrument will be constructed in the University of Manchester.

4. Further Developments. — It remains to be seen, experimentally, what field the instrument can use before the aberrations destroy the imaging process. The most obvious improvement is the replacement of a single lens by a multi-component lens in which all the geometrical aberrations are corrected, and the longitudinal chromatic aberration is given the greatest possible value. In its present form it seems that it would be useful for studies of fluorescence phenomena, and for low-resolution night-sky and astronomical observations. Whether it may come to be a serious rival to the Fabry-Perot etalon as an astronomical spectrometer is a matter for some doubt, but will clearly depend on the amount by which a well designed lens will improve the dispersion.

Bibliographie

[2] Rubens (H.) and Wood (R. W.), Phil. Mag., 1911, 21, 249.

INTERVENTIONS

H. H. Hopkins. — I think that the estimate of the size of field as 1/50 th of the focal length is an underestimate. It should be possible to obtain a field size of at least 1/10 th of the focal length, giving a 25 times increase in luminosity.

The question of coherence has been raised. If the illuminating cone has an aperture equal to that of the lens imaging the gratings, the transfer function will be closely enough that obtained for an incoherently illuminated grating. It might also be mentioned that one could use this type of system in tandem.

A. Lohmann. — As far as I remember T. Merton and F. H. Smith have used, or at least considered the use, of the longitudinal dispersion of a Fresnel zone
plate (FZP) for spectroscopic purposes. I guess they took one FZP as the object (spatially incoherently illuminated), and another identical FZP in the image plane, behind which the total flux was measured. The image formation was performed by a third FZP in the middle. Longitudinal squeezing provides for a change in $\lambda$. Lateral oscillation of the image FZP provides for temporal modulation of the wavelength in resonance, much like in SISAM instruments.

J. Katzenstein. — I think that the real application of this instrument would be in the extreme ultra-violet and soft X-ray region of the spectrum using a self-supporting zone plane as the lens. Diffraction effects of the grille are negligible for these short wavelengths ($\lambda R \ll 1$). Also as the focal ratios are necessarily of the order of $10^2$ to $10^3$ because of the large value of $r/\lambda$, the image defects of the zone plate are not significant.