A Novel Crossed Fizeau Interferometer

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A novel crossed Fizeau interferometer

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A new concept in optical spectroscopy is described which involves orthogonally mounted Fizeau interferometers. Data are output as two-dimensional images, in which the intensity of input light of a given wavelength is encoded at a specific x, y coordinate. Quantification may be obtained by means of an image detector and processor. A proof-of-principle experiment has been carried out. The possibility of a high-resolution compact spectrometric device is discussed.

1. Introduction

The purpose of this paper is to introduce a new concept in optical spectroscopy that yields reasonable resolution and spectral range in a compact package and is suitable for use in adverse environments. Our research began with the idea of a silicon-based optical imaging device (OID) as a spectroscopic detector (Bilhorn *et al.* 1987*a*, *b*). These sensors have the benefit of viewing all elements of the spectrum simultaneously, thus obtaining a multichannel advantage, while eliminating the need for mechanical scanning. The obvious way to use an OID is to place it at the exit plane of a spectrograph. Generally, linear photodiode arrays (PDA) with 'slit-like' apertures have been used for this purpose (Callis *et al.* 1981), and ultraviolet/visible (UV/VIS) absorption spectrometers based on this principle are commercially available (Hopkins *et al.* 1979). Such instruments have indeed proven more rugged than their mechanically scanned counterparts and have low noise levels as well. However, PDA-based spectrophotometers still occupy considerable space due to the spectrograph. Although such devices can be scaled down (Fuh & Burgess 1987), they eventually reach the limitations that arise from the finite size of the detector elements and the need to use a ruled grating of a sufficient number of lines to achieve the desired spectral resolution.

These limitations led us to develop a compact, planar absorption spectrometer based on multibeam interferometry (Pfeffer *et al.* 1984). In this device, light from a tungsten-halogen lamp was collected and collimated by a lens, and passed through a cuvette containing the sample. The transmitted light was then analysed by a wedge interference filter whose wavelength of maximum transmission varied continuously along the vertical (long) axis of the cuvette. Immediately behind the interference filter a vertically oriented array of photodiodes was placed. Thus each photoelement observed a different portion of the spectrum. Preliminary results showed adequate performance: spectra of typical absorbers compared well with conventional instruments; the dynamic range of the instrument extended over four orders of magnitude, and detection limits were in the parts per billion (thousand million) range (Pfeffer *et al.* 1984).

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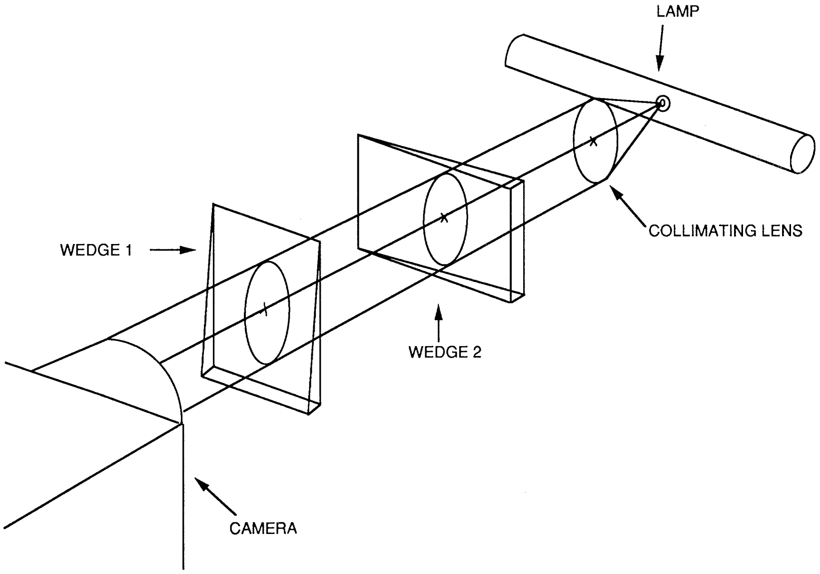

Figure 1. Principle of operation.

A major advantage of this spectrometer was its extreme compactness. In essence, the small size arises because we substituted multibeam interferometry for dispersion. The wedge filter obtains its resolution via a highly folded optical path, which results in a greatly reduced dimension. Thus the instrument may be thought of as series of Fabry–Perot interferometers, each of which varies systematically in gap distance, and therefore, wavelength. Also, we have eliminated mechanical scanning by the use of a photodiode array, which additionally allowed observations of all wavelengths simultaneously.

The wedge filter spectrometer concept provides a useful starting point for a rugged, compact instrument. However, there is still one limitation that is shared with polychromator-based instruments: for a given resolution, the higher the wavelength coverage desired, the greater the length of the photodiode array required. Our solution to the dilemma is to 'fold' the spectrum onto the focal plane and detect the resultant image with a two-dimensional PDA. At least two methods for doing this have been used for dispersion-based wavelength analysers: (*a*) linear dispersion followed by folding with the aid of several mirrors (Filkel & Pardue 1977), and (*b*) two-dimensional dispersion, with low- and high-resolution dispersers mounted in orthogonal directions. Instruments based on this latter concept are known as Echelle spectrographs (Harrison 1949). In these systems, a coarse diffraction grating is operated in high order to give high resolution, but with multiple overlapping orders. The second dispersion is accomplished with either a diffraction grating or a prism, oriented to disperse at right angles to the first. By this means, the second (low resolution) device acts as an order sorter for the first (high-resolution) device. The format of the spectrum is conveniently folded for detection with a two-dimensional OID (Bilhorn & Denton 1989).

Here, we demonstrate that a two-dimensional interferometric analogue to the Echelle spectrograph can be constructed. The basic idea is shown in figure 1. Our instrument consists of two Fizeau interferometers (Fizeau 1862). One is mounted so that its cavity is wedged in the vertical direction with large average cavity dimensions, thus yielding high resolution along the vertical axis, but with multiple overlapping orders. The second Fizeau interferometer is mounted so that its cavity is wedged in the horizontal direction with small cavity dimension, thus yielding low resolution, but acting as order sorter for the high-resolution wedge.

2. Theory

The crossed Fizeau system may be considered as a two-dimensional array of elemental, non-interacting, two-cavity Fabry–Perot etalons. For each of these, the transmission function for monochromatic light of wavelength λ incident normally is given by

$$T = [1+4r_x(1-r_x)^{-2}\sin^2(2\pi n_x d_x/\lambda)]^{-1}[1+4r_y(1-r_y)^{-2}\sin^2(2\pi n_y d_y/\lambda)]^{-1}, \quad (1)$$

where r is the reflectivity of the plates, and n the index of refraction of the material in the plate gaps, d. The subscripts x and y refer to the coarse- and high-resolution wedges respectively.

For the first interferometer, we assume that the mirrors are tilted so that the plate gap, d_x is solely a function of the horizontal axis, x. Then, assuming the mirrors to be square and of characteristic dimension l, we can write that

$$d_x = d_{x_0}+s_x x \quad (2)$$

for $0 \leqslant x \leqslant l$, where d_{x_0} is the plate gap at the zero coordinate and

$$s_x = (d_{x_0}-d_{x_l})/l, \quad (3)$$

where d_{x_l} is the plate gap at coordinate $x = l$. Obviously, s_x is represents the slope of the plate gap against x-coordinate.

For the first-order wedge a given wavelength will be transmitted at location x given by the condition

$$\lambda = 2d_x. \quad (4)$$

Furthermore, suppose that this coarse wedge is operating in first order and the light is confined to a wavelength range ($\lambda_l \leqslant \lambda \leqslant \lambda_h$) which is less than the free spectral range, i.e.

$$\lambda_h - \lambda_l < \lambda_l. \quad (5)$$

For the second interferometer, the mirrors are tilted so that the plate gap, d_y, is solely a function of the vertical axis, y. Then, assuming square mirrors of characteristic dimension l,

$$d_y = d_{y_0}+s_y y, \quad (6)$$

where the terms d_{y_0} and s_y are defined analogously to the d_{x_0} and s_x terms. This wedge is assumed to be of larger spacing so that a number of orders, $m_a \leqslant m \leqslant m_b$ can satisfy the condition

$$m\lambda = 2d_y. \quad (7)$$

For the wavelength range $\lambda_l \leqslant \lambda \leqslant \lambda_h$, the orders will be confined to a range of integers the extrema of which obey the constraints:

$$m_a \leqslant 2d_{y_0}/\lambda_h; \quad m_b \leqslant 2(d_{y_0}+s_y l)/\lambda_l. \quad (8)$$

When the two interferometers are considered in series, as in equation (1), a particular wavelength is transmitted at a particular combination of plate gaps given by the equation

$$\left.\begin{matrix} d_y/m_a \\ \vdots \\ d_y/m_b \end{matrix}\right\} = d_x, \tag{9}$$

where m is constrained to the integer values defined above. Substitution of (2) and (6) in (9) results in an expression for the locations in the x, y plate where maximal transmission of light is located

$$y = \begin{cases} (1/s_y)\{s_x m_a x - (d_{x_0} m_a - d_{y_0})\}, \\ \qquad \vdots \qquad\quad \vdots \qquad\quad \vdots \\ (1/s_y\{s_x m_b x - (d_{x_0} m_b - d_{y_0})\}, \end{cases} \tag{10}$$

for the range $0 \leqslant x \leqslant l_0$. Equation (10) informs us that the output format of two-dimensional Fizeau is a series of stripes located in the x, y plane, each one of which corresponds to a specific order m. As with any two Fabry–Perots of dissimilar gaps in series, a transmission profile is achieved that resembles that of the high-resolution plates, with a free spectral range which resembles that of the low-resolution plates. This output format bears a considerable resemblance to that produced by an Echelle spectrograph. And, quantities analogous to dispersion are clearly derivable. It should be noted, however, that equation (10) is a crude approximation that ignores 'parasitic' resonances arising from high orders transmitted by the high-resolution Fabry–Perot that are not completely blocked by the low-resolution Fabry–Perot. It should also be noted that the width of each order in the x dimension is limited by the low-resolution Fabry–Perot.

2.1. *Experimental*

A prototype fibre optic flame emission analyser has been constructed and tested. A schematic diagram of the device is given in figure 2. As the coarse interferometer, we used a wedge interference filter (Pfeffer *et al.* 1984), which functions as a first-order Fizeau in interferometer in the region 400–700 nm with a resolution of 15 nm. As the fine wedge filter, we used a Burleigh Model RC 110 Fabry–Perot interferometer. This device was wedged by suitable adjustment of the alignment knobs. Fine tuning was accomplished with piezoelectric spacers controlled by a Burleigh Model RC-43 programmable ramp generator.

Low-pressure mercury and neon lamps were used simultaneously as reference line emission sources. To illustrate the instrument's capability for on-line atomic emission experiments, a Beckman Model 9125 oxygen/acetylene and nebulizer unit was used as an analytical atomic emission source. Both lamps and the flame were simultaneously imaged into the interferometer by means of a bifurcated fibre optic light guide. For some experiments a low-power He–Ne laser was used as an additional reference light source. Because of geometric constraints, a transfer lens was used between the fine and course wedges. The two-dimensional interferogram was imaged onto the surface of an intensified charge injection device (ICID) camera (Xybion, Model ISG-02). For quantitative image capture and processing, a Quantex QX-7 system was used. This allowed real time averaging, background subtraction and display of results in various formats.

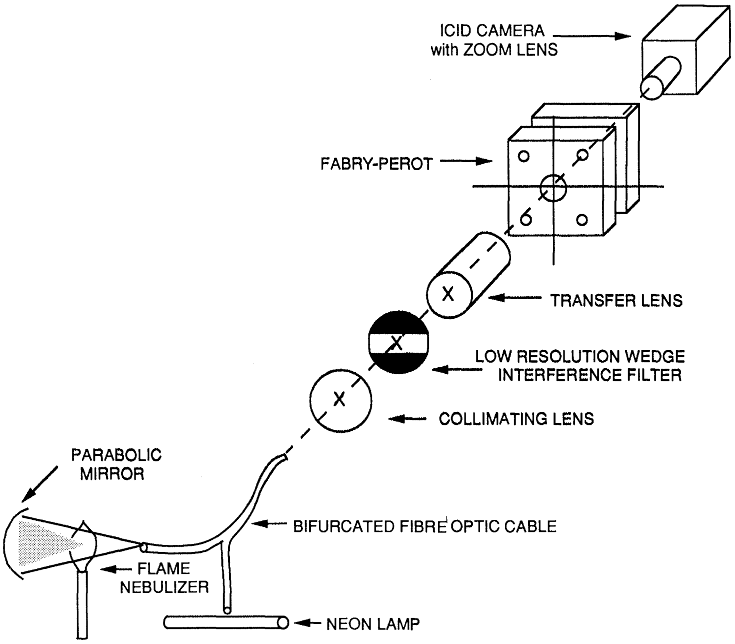

Figure 2. Schematic of double-wedge interferometer prototype.

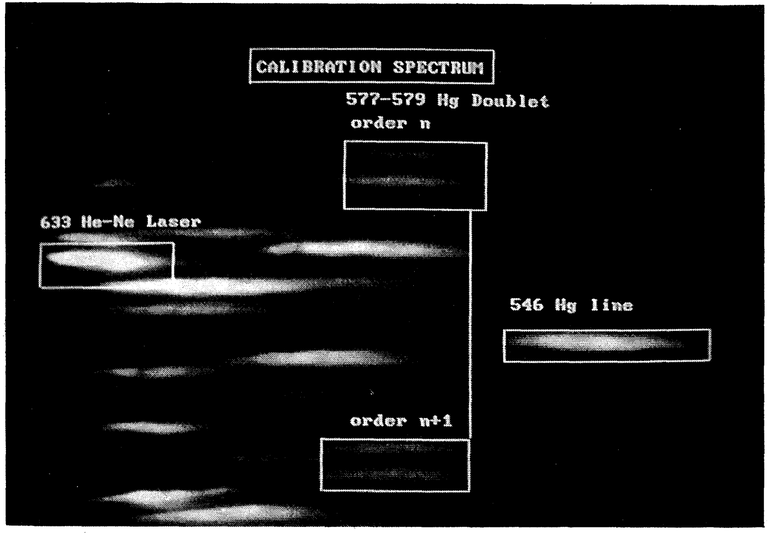

Figure 3. Video monitor output of prototype interferometer viewing mercury and neon lamps.

2.2. *Results and discussion*

Figure 3 shows the output of the two-dimensional interferometer, displayed as labelled television image, photographed from the surface of the image processing monitor. Here, only the line sources are being viewed. To improve the signal-to-noise ratio, approximately 40 images were co-added, and an equal number of blank images were subtracted. The vertical dispersion, as provided by the Fabry–Perot, yields approximately 10 nm across the image sensor face for each order. The horizontal

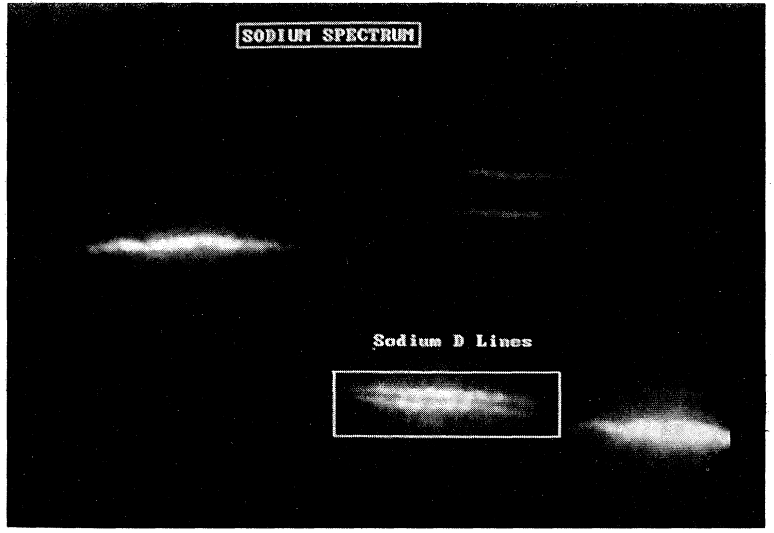

Figure 4. Video monitor output of prototype interferometer viewing mercury lamp and flame emission of sodium.

dispersion, as provided by the wedge interference filter, yields approximately 100 nm across the image sensor face. Clearly, in accord with theory, the resolution in the horizontal direction is far less than that in the vertical direction. At present, the resolution attained in the vertical direction (0.5 nm) is far less than that expected from a Fabry–Perot operated in approximately 50th order with high reflectivity plates. This is ascribed to local imperfections in optical quality.

Figure 4 shows the output of the interferometer when it is simultaneously viewing the mercury lamp and the flame, while a solution of 100 p.p.m. (parts per million by mass) of sodium and 1000 p.p.m. of lithium is being nebulized. The sodium doublet at 588–591 nm is clearly resolved. Further experiments demonstrated that the detection limited for Na, expressed as twice the standard deviation in the background, was 20 p.p.b. (parts per thousand million). This appeared to be a limitation of the flame, as the fraction of the noise contributed by the intensified array was very small. Indeed, the manual for the nebulizer and flame unit claimed a detection limit of 20 p.p.b. Improvements in sensitivity will undoubtedly be forthcoming with better nebulizers, flames, and optics.

The above results show the feasibility of a crossed Fizeau interferometer for practical spectroscopy, and encourage the belief that a compact spectrometer can be constructed based on this principle. In fact, an even smaller spectrometer could be devised by integrating, via microcoating techniques, the entire interferometer system onto the surface of a CCD imager. A system such as this would offer wide spectral range simultaneously with high resolution, ruggedness, and stability, together with lightness of weight and ease of manufacture.

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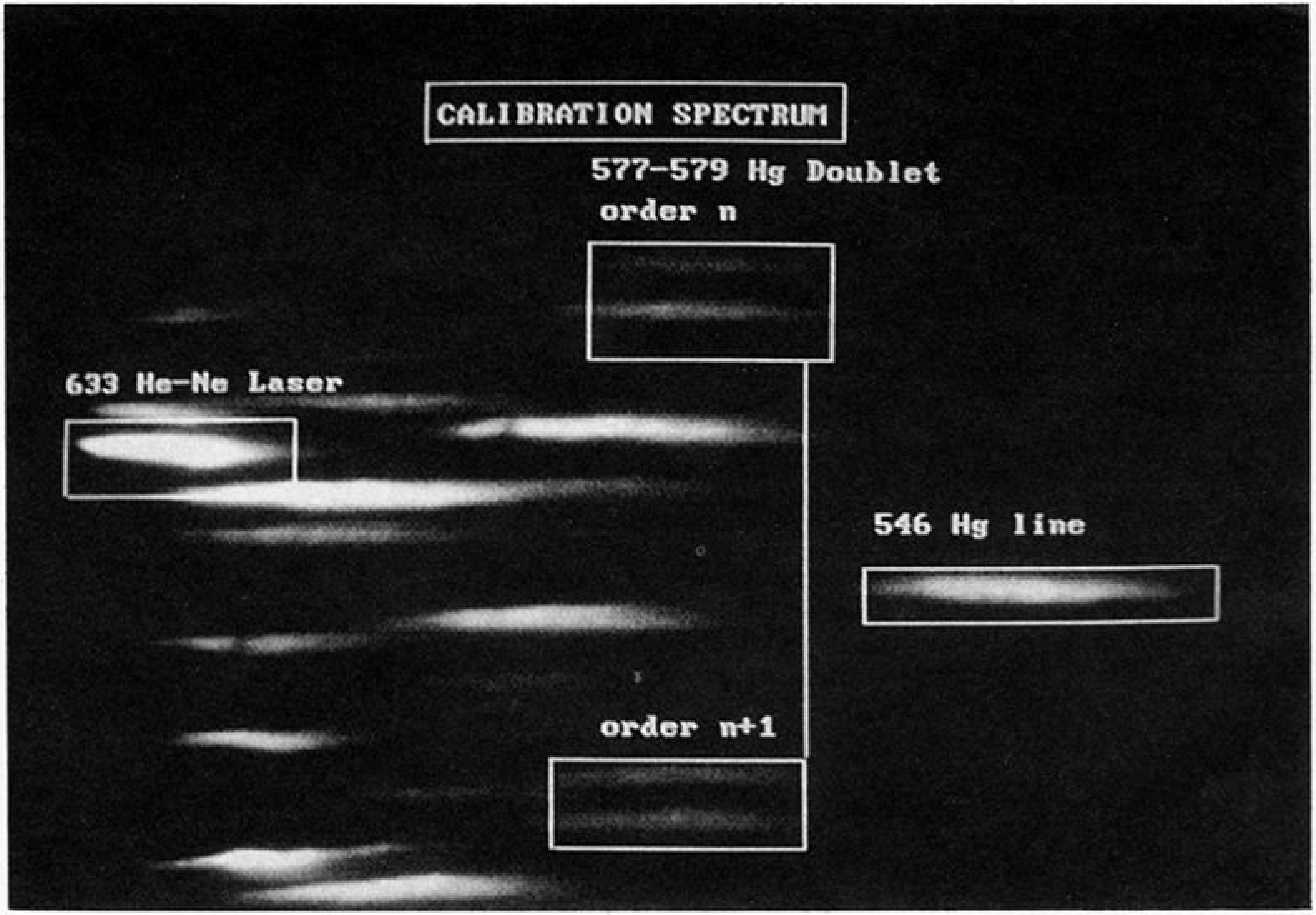

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