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POLARISED INTERFEROMETRIC SPECTROMETRY FOR THE MILLIMETRE AND SUBMILLIMETRE SPECTRUM

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Abstract—A method of interferometric spectrometry based on polarising beam-splitters is described. This allows operation over a wide range of spectral frequency without strong variations in efficiency, and also the suppression of the mean-level of the interferogram, spurious modulation of which is a major source of error in conventional methods. Interferograms obtained with this kind of spectrometer, in the far infra-red, are presented.

SOME of the potential of Fourier-transform spectrometry has been realised recently, especially in the far infra-red.[1–3] There are, however, difficulties in obtaining spectra over several octaves with a single beam-splitter if the low-frequency millimetre-wave spectrum is to be included. The thin-film dielectric beam-splitter and the lamellar beam-splitter have efficiencies which vary with frequency as expressed in Fig. 3 of Ref. (3). In addition, spurious modulation of the large background level can be confused with true interferometric modulation. In this note we describe a somewhat different method of interferometry which introduces a beam-splitter which may have high efficiency from well below 2 cm^{-1} to well above 100 cm^{-1}, and in which the background level can be suppressed.

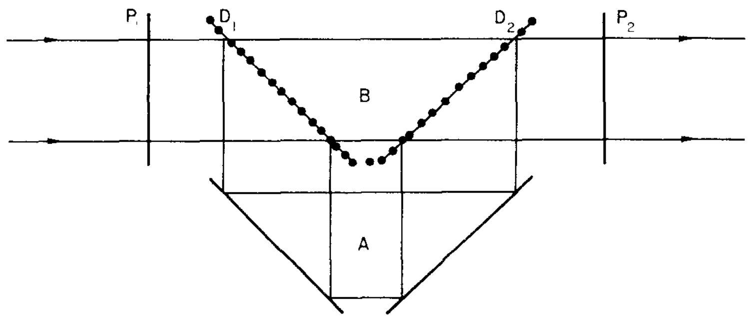

FIG. 1

Figure 1 illustrates the essential features of the method and Figs. 2 and 3 illustrate simpler or more effective ways of realising it. Referring to Fig. 1, a collimated beam is plane-polarised at P_1 in the plane at 45° to the normal to the page. It is then divided by a flat wire-grid polariser, D_1, into beam A polarised with its E-vector normal to the paper and beam B polarised at 90° to A. A and B are recombined at the wire-grid D_2 and the

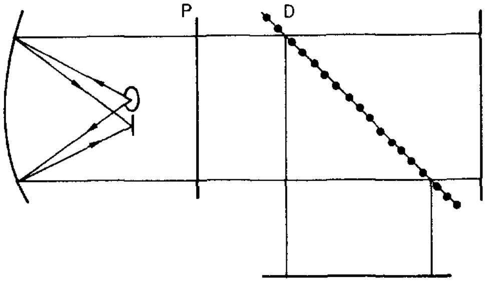

FIG. 2

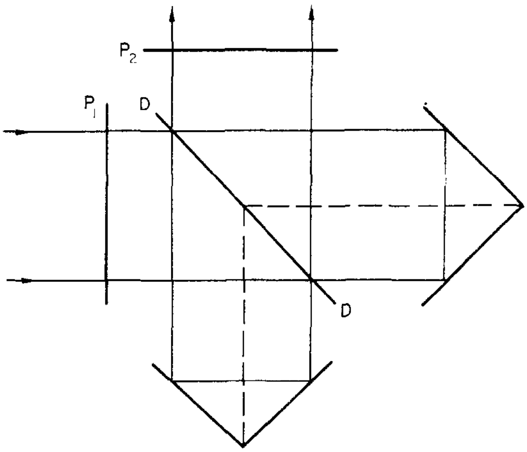

FIG. 3

combined beam finally passes through polariser P_2 which has its axis parallel to that of P_1 or at 90° to that direction. With a monochromatic source, the beam is elliptically polarised after recombination at D_2 with an ellipticity varying periodically with increasing path-difference between beam A and beam B. After P_2 the beam is plane-polarised with an amplitude which varies periodically with path-difference in the same way as in a Michelson interferometer (including the same intensity, assuming an unpolarised source). That is (see Appendix A)

$$I_p = \frac{I_0}{2}(1 + \cos\Delta)$$

and

$$I_t = \frac{I_0}{2}(1 - \cos\Delta)$$

where $\Delta = (2\pi/\lambda)x$ (where x is the path difference) and I_0 is the intensity of the plane-polarised beam incident on D_1. The case I_p is for parallel P_1 and P_2 and I_t is for crossed P_1 and P_2.

Wire-grids can have reflection and transmission coefficients approaching 100% for the appropriate planes of polarisation, from effectively zero frequency up to roughly $(1/2d)$ cm^{-1}, where d cm is the spacing of the wires. Grid polarisers have been deposited on polyethylene substrates[4] with spacings equivalent to $> 500\,cm^{-1}$. Grids on Mylar film with spacings corresponding to a frequency of $> 150\,cm^{-1}$ are available commercially[5] and can be rendered very flat on stretchers. With a very simple abrasion technique we have made large polarisers from metallised Mylar films (see Appendix B) and have used them as polarising beam splitters to test the method described above at frequencies between 10 and 80 cm^{-1}, as recorded below.

Among the advantages which should be realised with a polarising interferometer are

(i) an increased spectral range with a single beam divider.

(ii) the possibility of making refractive index measurements[6] at millimetre wavelengths (the lamellar beam-splitter previously used at low frequencies does not separate the beams spatially).

(iii) a background interferogram could be taken at the same time as that for the sample if the sample follows the analyser P_2 and a second detector monitors the beam reflected from P_2.

(iv) the complementary nature of the interferograms for the two orthogonal orientations of the polariser or analyser makes it possible to eliminate the high mean-level of an orthodox interferogram (together with the errors which spurious modulation of the mean-level introduces) by alternating the orientation of P_2 or P_1 instead of chopping or, alternatively, by using two detectors in opposition, one receiving the beam transmitted by, and the other that reflected by, P_2. In either case the output for a monochromatic source is:

$$I_p - I_t = I_0 \cos\Delta$$

which oscillates about the true zero-level.

Figures 2 and 3 respectively illustrate how interferometers might be constructed to operate in the manner described here. In Fig. 3, corner reflectors are used as rotators, the wires in the divider being at 45° to the paper. If the grid of the beam divider is deposited on one side of a dielectric film, a balanced system having more exact symmetry for the two beams can be designed, using a double beam-divider, to give more symmetric interferograms.

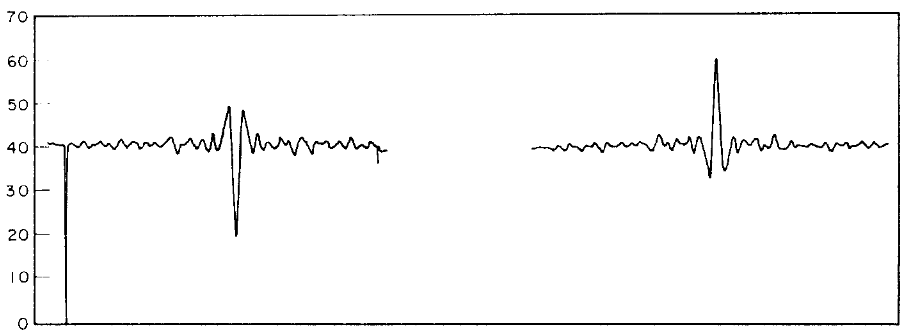

FIG. 4. Example of inversion of an interferogram.

Figure 4 shows the inversion of an interferogram obtained with a polarising interferometer on rotating the analysing polariser through 90°. Figure 5 shows an interferogram obtained with a balanced system (note the true zero level). The interferometer used employed

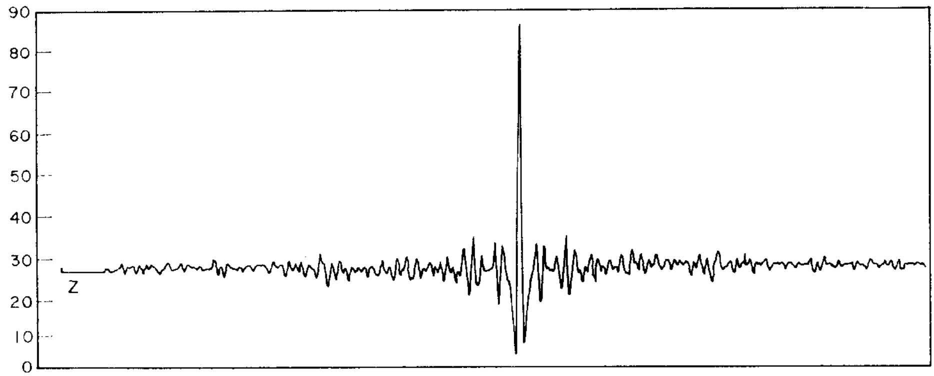

FIG. 5. An interferogram for transmission through approximately 1 m of air, for 2 cm maximum path difference. Z indicates the true zero-level (an off-set voltage was added at the recorder for convenience in recording).

the easily fabricated polarisers described in Appendix B and, when transformed, shows the usual water-vapour absorption lines over the range 10–80 cm^{-1}, where the filter cuts off.

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APPENDIX A

Let $\hat{n}$, $\hat{t}$, $\hat{p}$ be unit vectors in directions normal to the paper ($\hat{n}$), in the plane of the paper and transverse to the direction of propagation[9] ($\hat{t}$) and in direction of the optical axes of P_1 and P_2 ($\hat{p}$). The **E**-vectors for a monochromatic source are then:

Incident on a beam-divider,

$$\mathbf{E}_i = a\hat{p}\cos\omega t = \frac{a}{\sqrt{2}}\hat{n}\cos\omega t + \frac{a}{\sqrt{2}}\hat{t}\cos\omega t.$$

Leaving beam-combiner,

$$\mathbf{E}_j = \frac{a}{\sqrt{2}}\hat{n}\cos(\omega t + \Delta_A) + \frac{a}{\sqrt{2}}\hat{t}\cos(\omega t + \Delta_B)$$

Leaving polariser P_2,

$$|\mathbf{E}_0| = \mathbf{E}_j\cdot\hat{p} = \frac{a}{2}[\cos(\omega t + \Delta_A) + \cos(\omega t + \Delta_B)]$$

$$= a\cos(\omega t + \bar{\Delta})\cos\frac{\Delta}{2}$$

where Δ_A and Δ_B are the phase shifts for the beams A and B, $\bar{\Delta}$ is the mean of Δ_A and Δ_B and $\Delta = \Delta_A - \Delta_B = (2\pi/\lambda)x$ where x is the path-difference. The emergent intensity is thus

$$I_p = \langle|\mathbf{E}_0|^2\rangle = \frac{a^2}{2}\cos^2\frac{\Delta}{2} = \frac{a^2}{4}(1 + \cos\Delta)$$

If the axis of P_2 were at 90° to P_1 instead of parallel,

$$\mathbf{E}_0 = \mathbf{E}_J \cdot \hat{\mathrm{p}}\,' \text{ where } \hat{\mathrm{p}} \cdot \hat{\mathrm{p}}' = 0 \text{ and hence}$$

$$I_t = \frac{a^2}{4}(1 - \cos\Delta).$$

APPENDIX B

We have found that reasonably efficient far infra-red polarisers which are adequate for many applications are easily fabricated by scribing an aluminised polyethylene terephthalate film ('Melinex' or 'Mylar') using emery paper as a tool to cut, in effect, a random multistart thread.

The aluminised film is wrapped tightly around a metal cylinder, clamped along its edges in a longitudinal slot, and mounted in a centre lathe. The thread is scribed by a 2 cm strip of fine grade ('Crocus') emery paper backed by a firm slab of plastic foam, using a fine feed and a cutting speed of about 80 m sec^{-1} with white spirit as a lubricant. In this way polarisers up to 30 cm square have been made. Marking the cylinder with a pencil lead along its surface helped in determining the pressure required to remove enough of the aluminum in a single pass. This marking should be just visible in a completed polariser.