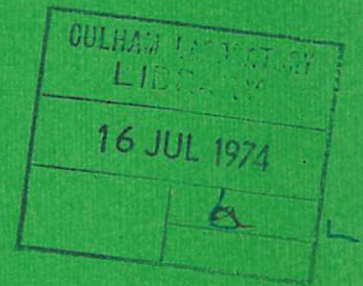


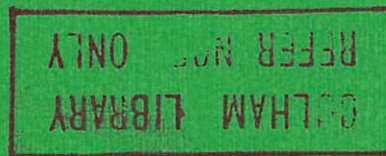


UKAEA RESEARCH GROUP

Report



A GENERAL PURPOSE CONTINUOUS
OBSERVATION INFRA-RED VIEWER



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CULHAM LABORATORY
Abingdon Berkshire
1974

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A GENERAL PURPOSE CONTINUOUS OBSERVATION
INFRA-RED VIEWER

S A HAMADTO^{*}

A B S T R A C T

A general purpose, cholesteric liquid crystal infra-red viewer has been constructed. The device, which is portable, cheap and simple to make and operate, has interchangeable screens and temperature bias facilities. It can detect power levels from a few tens of milliwatts to a few watts per square cm. It affords a very convenient means for qualitative infra-red viewing, e.g. visualization of laser modes and interference patterns including Fabry-Perot fringes, optical alignment and determination of lens focal lengths at the infra-red.

* The author is on attachment from Sussex University. He is supported by a joint grant from the University of Khartoum and the British Council.

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January 1974

SBN: 85311 023 9

INTRODUCTION

Since the first demonstration by Hansen et al⁽¹⁾ of the effective use of a cholesteric liquid crystal viewer for the observation of infra-red patterns, other more sensitive and elaborate devices have been developed^(2,3,4). To achieve maximum sensitivity, fast rise-time and optimum readout, systems using built-in cameras with evacuated enclosures were constructed. Such systems, which no doubt give the best results, are rather expensive and, where simple infra-red imaging is required, may prove too sophisticated for the purpose in hand. In any case, there are situations where a continuous, direct observation of an infra-red pattern (e.g. a laser mode or an interference pattern) is desirable. Some of the popular methods for doing this are the very elementary (sometimes dangerous) uses of smouldering paper and glowing fire bricks. Use of the more novel phosphor image plates seems to be discouraged by the relatively high cost incurred in a detector of limited and only qualitative use.

We have developed a portable, cholesteric liquid crystal infra-red viewer which we believe is a useful substitute for the above techniques in the range of application mentioned. It is cheaper and much more sensitive (by at least one order of magnitude) than the most sensitive phosphor image plate. The design of the prototype is quite flexible, and many alterations can be introduced, with advantage.

REVIEW OF THE PROPERTIES OF LIQUID CRYSTALS⁽⁵⁾:

We present in this section a discussion on liquid crystals, to illustrate the major principles of operation of the detector, which is basically a liquid crystal⁽⁵⁾ of the cholesteric type supported on a suitable membrane. We hope this will also clarify the slight confusion associated with the use of the term 'liquid crystal'. For, although there are three different types of liquid crystals, the term tends to be used indiscriminately to describe one type where another may be meant.

1. History, Terminology and Classification:

As has been recognised, since the very early days of science, matter may exist in three possible states of aggregation - the solid, the isotropic liquid, and the gas (the fourth, plasma, state does not concern us in this discussion as we are dealing with temperature ranges much lower than those giving rise to atomic dissociation). The solid state may be either crystalline, when the solid is comprised of a regular three-dimensional array of molecules or ions, or amorphous. In the latter case, the regular geometric arrangement is absent and there exists a random, though well-knit, arrangement of the units in the solid state. On the other hand, the crystalline solid may be regarded as the most highly ordered

state of aggregation in which matter exists. The majority of organic and inorganic compounds give rise to solid states which are crystalline and indeed those crystalline characteristics and properties (e.g. anisotropy, etc.) are often present even though the solid may appear on casual inspection to be an amorphous powder.

On passing from the crystal to the isotropic liquid then to the gas phase, the degree of molecular order decreases, and the transitions from crystal to liquid and from liquid to gas occur, particularly in the case of organic compounds, at well-defined temperatures which are characteristic of a particular compound.

However, towards the end of the nineteenth century, a number of newly prepared compounds were found to exhibit new and peculiar melting phenomena. For example, in the case of cholesteryl benzoate, the crystals melted perfectly sharply at 145.5°C , but the melt was quite definitely opaque. Not until the temperature was increased to 178.5°C did the opacity disappear suddenly, giving the true isotropic liquid. Whilst such 'intermediate', usually turbid, states were fluid to a greater or lesser extent, they also exhibited anisotropic properties when viewed in thin section between crossed polaroids. Their characteristics were therefore partly those of the crystalline solid and partly those of the liquid. The early workers coined the name 'fluid crystals' or the more modern, liquid crystals, for them.

As more of the properties of these liquid crystals became known, it was obvious that here indeed was a new state of matter, and the new name mesophase was introduced to stress the intermediate nature of these states of matter. (The term derives from the Greek mesos, between or intermediate, and phasis, a state or phase.) This term and the associated terms mesomorph, mesomorphism, mesomorphic and mesoform are indeed widely used today, although references to liquid crystals are still frequently used in the literature.

Three different types of mesophase are distinguishable through their different optical properties. Very briefly they are:

- (a) The smectic mesophase:- a turbid, viscous state, with certain properties reminiscent of those found for soaps.
- (b) The nematic mesophase:- a turbid but mobile state. On surfaces such as glass, the mesophase frequently adopts a characteristic "threaded" texture, clearly visible between crossed polaroids. (This incidently, is the type of liquid crystal used in some alphanumeric displays).
- (c) The cholesteric mesophase:- a turbid and mobile mesophase, exhibiting some unique optical characteristics, quite different from those

of the smectic and nematic mesophases. The majority of compounds exhibiting this type of mesophase are derived from cholesterol or other sterol systems.

Mesophases are most commonly observed when a suitable compound is heated to a temperature above that at which the crystal lattice is stable. This type of mesomorphism is called thermotropic, and the mesophase is then characterised by transition temperatures and by a mesomorphic range (or ranges). The sequence of changes may be illustrated as:

Crystals $\xrightarrow{T_1}$ Mesophase $\xrightarrow{T_2}$ Isotropic liquid

These transitions are usually, but not necessarily, reversible. Furthermore, a compound may exhibit the phenomena of polymesomorphism, where two different mesophases appear. A possible transition is

Crystal $\xrightleftharpoons{T_1}$ Smectic $\xrightleftharpoons{T_2}$ Cholesteric $\xrightleftharpoons{T_3}$ Isotropic.

We are now in a position to proceed to a discussion of the mesophase of interest to us, viz the cholesteric mesophase. The other two will not be further mentioned.

2. The Cholesteric Mesophase:

The property of this material which makes it adaptable for an imaging device is its iridescent colour of reflection when illuminated by white light. The light is scattered by the mesophase much as a normal crystal scatters x-rays. However, this material is unique in having only one wavelength scattered (no higher orders). The wavelength of the scattered light varies as a single-valued function of temperature, thus making possible a reversible temperature indicator.

We would like to stress that this state of affairs arises when the mesophase assumes a particular 'texture'. In general the birefringent patterns of mesophases are referred to as 'textures', a term which is preferable to structure, and a particular type of mesophase will adopt one of a limited number of textures which may be used to establish its identity. These textures, which are essentially structural modifications in the mesophase, can be observed by examining sections of the mesophase (under a microscope) mounted between glass surfaces.

The two common textures adopted by the cholesteric mesophase are the focal conic texture and the Grandjean plane texture. In the former, one observes focal-conic groups. (For an ellipse and an hyperbola to be related as focal-conics, the locus of the vertices of the cones of revolution whose bases are the ellipse must be the hyperbola which passes through the foci of the ellipses, and whose plane is at right angles to the plane of the ellipse).

It is the Grandjean plane texture which gives rise to colour reflection. If a drop of a cholesteric compound which has adopted this texture (either spontaneously or through a slight mechanical disturbance of the focal conic texture) is examined, it is seen to consist of flat planes which are exactly parallel to one another and to the plane of the supporting surface. These planes are of equal thickness when at the same temperature. By studying the Newton rings obtained from such preparations, Grandjean⁽⁵⁾ found that these layers are about 1880 Å thick at the lower temperature limit for the cholesteric mesophase, increasing to 2180 Å as the temperature is increased towards the cholesteric-isotropic transition point. The colour observed by reflection by the plane texture depends upon:

(1) The temperature of the preparation and the nature of the compound. This is the property used for thermal imaging applications. Related physical problems will be discussed later.

In many cases (cholesteryl esters and the commercially available liquid crystals mixtures), the colour of the reflected light is violet when the plane texture is produced at a temperature just below the transition from the isotropic liquid. As the temperature falls, the colour of the reflected light changes gradually to light blue, to blue, to green, to yellow, to red, giving finally reflected light whose wavelength is in the infra-red, which is not visible. The rapidity with which these colours replace one another varies considerably from one compound to another, and each particular preparation has got to be individually 'calibrated' to get a colour to temperature relationship. Since these colours are observed upon reflection, they must be viewed with a black background.

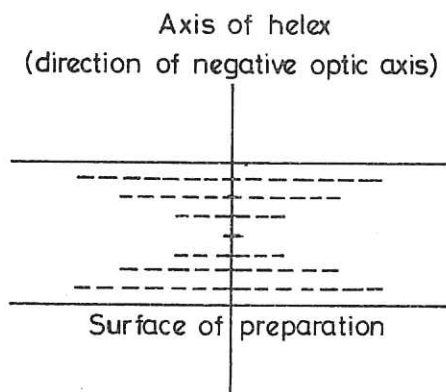
(2) The angles between the incident and reflected rays and the normal to the preparation. The wavelength of the reflected light is in fact a maximum when the two rays are normal to the preparation and decreases as the angles between the two rays and the normal to the preparation increase. The relationship between the wavelength of the reflected light and the angle of the incident beam to the normal can be explained approximately by the Bragg diffraction relationship. The coloured, reflected light is therefore a function of the structure of the texture.

We now mention another related property (to colour reflection) which, even though it does not concern our particular physical application much, has to be considered if any explanation relating to the actual molecular structure is attempted. This concerns the high optical rotary power of the Grandjean plane texture. If the wavelength of the incident light is less than that of the light scattered, at maximum intensity, normal to the surface of the preparation, the

plane of polarization of the incident light is rotated (to the left or right depending on the class of compound - whether laevo - or dextro-) upon transmission⁽⁵⁾. If now the wavelength of the incident light is gradually increased an inversion of the direction of rotation of the plane of polarization of the light occurs (to the right or left) when the wavelength exceeds that of the light scattered at maximum intensity. The wavelength of inversion (λ) varies with temperature and from one compound to the other; and may be anywhere from the ultra violet to the infra-red. In general, starting at short wavelength of incident light, the optical rotary power decreases as the wavelength of light increases, becoming zero at a certain critical wavelength (λ), and then increasing again as the wavelength of the light increases still further.

Typical values of the rotation introduced are of the order 1000° per mm, and can be as high as 30000° per mm. These immensely high optical rotary powers cannot be associated simply with the fact that the molecules are optically active, but rather with the way in which these molecules are arranged in the mesophase.

The molecular aggregation in the cholesteric layers is not completely understood. However, De Vries (ref 21 in (5)) offers a satisfactory model which explains the two major properties. He regards the cholesteric mesophase, in its plane texture, as being comprised of birefringent layers of refractive index n_1 and n_2 and thickness b . These layers are piled one above the other in such a way that the electric axes of the molecules rotate like a screw (see Fig a.) on passing through successive layers. A twisted structure is therefore envisaged,



Molecules represented by - - - - -

Major axes of the molecules twisted through 180° about the axis of the helix.

having a pitch p . (This pitch varies with temperature, giving rise to selective reflection of light.) De Vries also uses a mean refractive index, $n = \frac{n_1+n_2}{2}$ and a relative birefringence, $\alpha = \frac{n_2-n_1}{n}$. Applying the electromagnetic theory of light, he illustrates that the observed properties of the texture are independent of b provided

$$b \gg p,$$

and that a wavelength of light $\lambda = pn$ must exist, for which such a system will give a particularly intense, selective reflection of circularly polarised light. Moreover, he shows that this reflection will be marked in the spectral range $\lambda (1 - \alpha/2)$ to $\lambda (1 + \alpha/2)$. Out with this range, the preparation will have a considerable optical rotary power with regard to transmitted light.

DESIGN FACTORS - CHOICE OF LIQUID CRYSTAL

In this and subsequent sections, we shall use the term 'liquid crystal' to refer to the cholesteric type, and, where necessary, to refer to the mesophase which has adopted the Grandjean plane texture.

The requirements we set ourselves to fulfil for the construction of a direct infra-red viewer are the following:

(a) A suitable liquid crystal:

Most individual cholesteric liquid crystals have a mesomorphic range which is too wide for imaging applications e.g. Cholesteryl oleate $17^{\circ} - 50^{\circ}\text{C}$. Fortunately, some organic chemicals manufacturers^(6,7) have developed mixtures of individual compounds (the composition of which is a well-guarded secret!) with ranges as low as 1°C , from about 10°C to 50°C . These mixtures are particularly advantageous as they exhibit brilliant colour changes over their temperature range. We obtained mixtures from Eastman-Kodak⁽⁶⁾ and Westinghouse Corp.,⁽⁷⁾ in the form of 10% solutions (by volume) of the proper material dissolved in petroleum spirit. A suitable candidate for our purpose was the Eastman-Kodak 'Cholesteric mixture 35-41', which had the mesomorphic range 35°C to 41°C . This was preferred to mixtures having a shorter range (e.g. 1°C), as the colour sequence in the latter was too rapid for direct viewing. (These 1° mixtures, incidentally, are the ones used in the more sensitive detectors; see e.g.⁽³⁾). The operating temperature (crystal to mesophase transition temperature) of the $35^{\circ}-41^{\circ}$ mixture is also well above room temperature, so that temperature bias is achieved by heating only (see point (c) below).

(b) A liquid crystal screen:

The relation between the rise in temperature ΔT produced by an amount of heat Q to the heat capacity C during a steady state is given by

$$\Delta T = \frac{Q}{C} .$$

For a given Q , ΔT is large when C is small and therefore a thin screen (e.g. 2μ Mylar) is most sensitive. Such screens, with a metal coating on one face to increase the absorption of the infra-red, are employed in the more sensitive systems⁽³⁾. They are, however, not suitable for direct imaging for two

main reasons. First they are so sensitive that they are easily affected by the slightest temperature variation, produced for example, by air convection, and must therefore be housed in an evacuated enclosure. What we have in mind is a portable, simple system, which is not complicated by provision for a vacuum system. The second reason relates to spatial resolution and readout time, the latter being the time taken by an infra-red image to build to an exact replica of the object. In the forementioned thin screen, this readout time is very short, ~ 100 ms, and the exact image can only be observed by the use of a synchronised delayed camera - another complication we would like to avoid. A readout time suitable for direct viewing was taken as 30 seconds. During this time, a good spatial resolution must be maintained, and this in turn is limited by thermal conduction along the surface of the screen (radial conduction). One requires the transverse conduction to be higher than the radial, so that heat is conducted across the thickness of the screen more quickly than along it.

With these conflicting factors in mind we experimented with a few materials to find a suitable one. Compromise materials were found to be $1/16$ -inch perspex and/or 10^{-3} inch melinex, though in the case of the latter one had to exclude draughts from the vicinity of the screen when in use. Both, of course, introduced the implicit loss of sensitivity mentioned above. Their construction and mounting are discussed in part 3 of the next section.

(c) Temperature bias:

To bring the liquid crystal to the 'operating point', its temperature (and that of the screen onto which it is mounted), is kept at or near the solid-mesophase transition temperature. The field of view (against a black background) is then red, and any incident infra-red introduces a further temperature rise which brings about a colour change (orange, yellow, green and blue). The most convenient method of temperature bias is through electrical heating. However, air convection between the heater and the screen introduces non-uniform surface heating, so that the top part of the screen is hotter than the lower part. This was quite bad in our initial experiments where we found that to keep the lower half of the screen at a red colour, the top turned green - a temperature difference of about 3°C . This problem was eventually overcome through putting a heat diffuser, in the form of a thin copper plate, just before the screen.

Alternatively one may circulate thermostatically controlled water adjacent to the screen. This can be of advantage and we made provision in our design for the use of this method.

DESCRIPTION OF THE DEVICE

The main components are a main frame, a heater unit and a liquid crystal screen. We describe each of these separately and then discuss their assembly.

1. Main Frame

This is shown in Plate 1. It consists of a short Al-alloy cylinder 2" long, 4.0" OD, 2.9" ID, threaded at both ends. In the centre is a tapped hole into which may be screwed any suitable optical stand. An annular knurled cap fits on each end (ID 2.9"). One cap locks onto the liquid crystal screen, while the other supports a disc carrying either a heater element or two water fittings, depending on which method of temperature bias is to be employed. The main cylinder has provision to carry 'O' rings, so that the enclosure can be made water-tight.

2. The Heater Unit

Plate 2 shows the unit we constructed, comprising a nichrome spiral fixed onto a 3.6" diameter $\frac{1}{4}$ " thick sindanyo disc that fits onto the main frame and is secured by the screw cap. The copper plate, shown on the photograph mounted on a screw 3 cm away from the heater element, is the heat diffuser mentioned already. For supply a 6 V stepped down mains was used, in conjunction with a variable transformer for temperature control (D.C. with a rheostat is equally good).

3. The Liquid Crystal Screen:

Two screens (A and B), which could be used alternately on the main frame, were made. Screen A was a $\frac{1}{16}$ " perspex disc, 3.6" in diameter, while B was a 10^{-3} inch (1 thou.) melinex sheet sandwiched between two $\frac{1}{16}$ " perspex rings which were then screwed together. Both were blackened at the back by spraying with car matt-black paint in aerosol form.

To deposit the crystal layer, the screen of interest was mounted onto the main body and secured with the screw cap. It was then put on a perfectly horizontal platform. 1 cc of the Eastman-Kodak 'Cholesteric mixture 35⁰-41⁰' (a 10% solution by volume) was diluted with 5 cc of petroleum spirit and then gently poured over the screen. It was allowed to evaporate at room temperature and away from any draught. This process was vital in the making of the viewer and extreme care and patience were required when carrying it out. If for any reason the resulting layer was not satisfactory (e.g. non-uniform), some more of the solvent was added, gently shaken and then allowed to dry again. This last process was used to restore the uniformity of the coating after a few weeks use. The resulting liquid crystal layer was about 20 μ m thick, worked out as follows:

Area covered (determined by the I.D. of the screw cap)

$$= \left(\frac{2.9}{2} \times 2.54\right)^2 \times 3.142 = 42.8 \text{ cm}^2 .$$

Volume of liquid crystal used = 0.1 cm^3

$$\begin{aligned} \therefore \text{ thickness} &= \frac{0.1}{42.8} \text{ cm} \\ &= 2.3 \times 10^{-3} \text{ cm} \\ &= 2.3 \times 10^{-5} \text{ m} \\ &= 23 \text{ } \mu\text{m}. \end{aligned}$$

When the coating was dry, it was gently warmed under a 60 W bulb for a few minutes. This improved the colour contrast. The finished screen had to be protected from the atmosphere, as it showed a great affinity for dust!

4. Assembly

Plate 3 illustrates the assembly of the various units, which are from right to left: Screw cap, the liquid crystal screen, an 'O' ring, the main frame, another 'O' ring, the heater unit and finally the other screw cap. Plate 4 is a view of the assembled detector, mounted on a Hilger and Watts stand.

SOME DEMONSTRATIONS AND RESULTS

A type A screen was prepared, using the Eastman-Kodak 'Cholesteric mixture 35⁰-41⁰' on a perspex disc in the manner described above. The resulting layer (with a mesomorphic range 35⁰C to 41⁰C) lasted for about two weeks before it was found necessary to re-activate it.

Many demonstrations were carried out with this viewer, ranging from imaging flames and light bulbs ($2 \mu\text{m}$ - radiation) by germanium optics, determination of focal lengths of germanium lenses, to viewing modes of and interference patterns from a pulsed laser. We give now an account of some representative demonstrations. (The photographs shown were taken by the Culham Photographic Section and they are for the sake of illustration only. As mentioned earlier, this viewer is not normally intended for use with a camera.)

1. Visualisation of CO₂ Laser Modes

The beam from a 10 W/cm² CW CO₂ laser was attenuated by inserting five unpolished germanium plates in its path. The transmitted power, assuming a

transmission per plate of 40%, is given by

$$10 \times (0.4)^5 W \approx 200 \text{ mW/cm}^2 .$$

The laser modes were observed directly on the screen with the aid of an ordinary lamp (tungsten). A multitude of modes could be produced by turning the supporting screws of the exit mirror of the laser. At one stage lasing action was suppressed completely and then brought back by re-aligning the mirror. Plate 5 is a photograph of one of the many modes observed.

The 'readout time' for these images was about 15 seconds, and the image usually persisted for five to ten more seconds, after which radial heat conduction tended to spoil the spatial resolution, and the colours merged into each other. This was no serious disadvantage, for it was only necessary to shut off the infra-red beam for a few seconds to allow the detector to recover.

2. Infra-red Shadows - Interference Fringes

Plate 6 shows a photograph of the infra-red 'shadow' of part of a wire gauze, focused onto the screen by a 10 cm germanium lens.

The photograph of Plate 7 is a striking demonstration of the versatility of the detector. It shows interference fringes produced by a few minutes wedge in a germanium plate. This plate, originally used to attenuate the laser beam, was assumed to be parallel-faced, but quite accidentally, was found not to be so.

One can work out the wedge angle θ from the fringe separation, d , in the photograph. θ is given by

$$\theta = \frac{\lambda}{2nd}$$

where $\lambda = 10.6 \mu\text{m}$, n , the refractive index = 4 and $d = 0.2 \text{ cm}$ (the photograph has a magnification of 4)

$$\therefore \theta = \frac{10.6 \times 10^{-4}}{8 \times 0.2} = 6.6 \times 10^{-4} \text{ radians}$$

$$\text{or } \theta = 2.4 \text{ minutes of arc.}$$

3. Megawatt Pulses

As a further demonstration the detector was blasted with a 2 MW pulse from a TEA CO₂ pulsed laser. This was easily tolerated. The mode structure, beam geometry and even diffraction effects were clearly visualised. The pattern persisted for about 20 seconds. Provided the incident energy does not exceed 3 joules, such big pulses can be viewed without damage to the detector.

4. Alignment of a Fabry-Perot interferometer - Comparison with a phosphor image plate.

The alignment of a Fabry-Perot interferometer at the infra-red has always been difficult due to lack of means to visualise the fringes. Although we were not anticipating this, it turned out that such fringes could be observed on our viewer. Plates 8 and 9 show how they looked. The fringe spacing as observed was however much larger than expected. We concluded that there are other fringes in between those observed, which were not visible. But in any case that was an excellent starting point for a finer alignment of a Fabry-Perot interferometer.

The appearance of these fringes enabled us to carry out a comparison between the viewer and a phosphor image plate. No fringes could be observed on the latter and we estimate that the liquid crystal viewer is at least one order of magnitude more sensitive than the most sensitive phosphor image plate.

CONCLUSION

The system we have described is an immediate substitute for such elementary techniques for viewing infra-red beams as smouldering paper, burning sticks and glowing fire bricks. From what we have described, it is a very useful tool for the visualisation of laser modes, for viewing various interference patterns, and most important, for the alignment of a Fabry-Perot interferometer, at least coarsely. Its low cost, increased sensitivity and better spatial resolution are advantages over other thermal viewers, such as phosphor image plates.

ACKNOWLEDGEMENT

The many discussions with Dr David Evans are warmly acknowledged.

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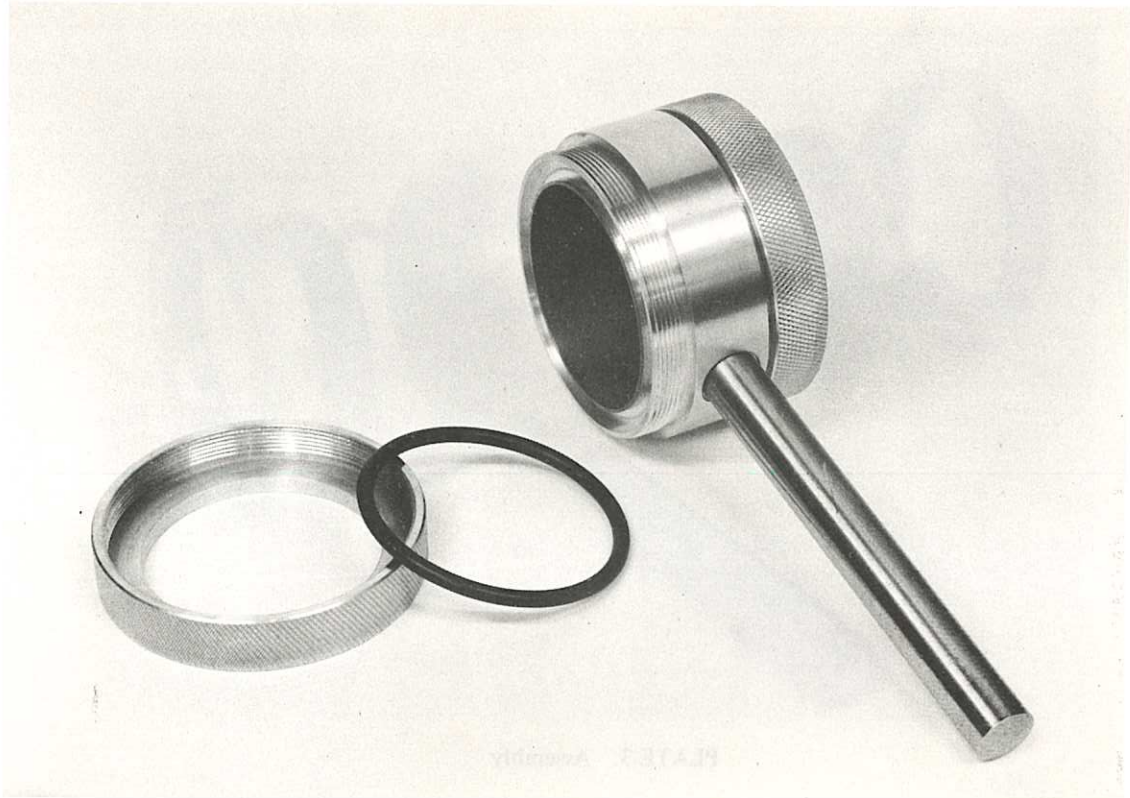


PLATE 1. Main Frame

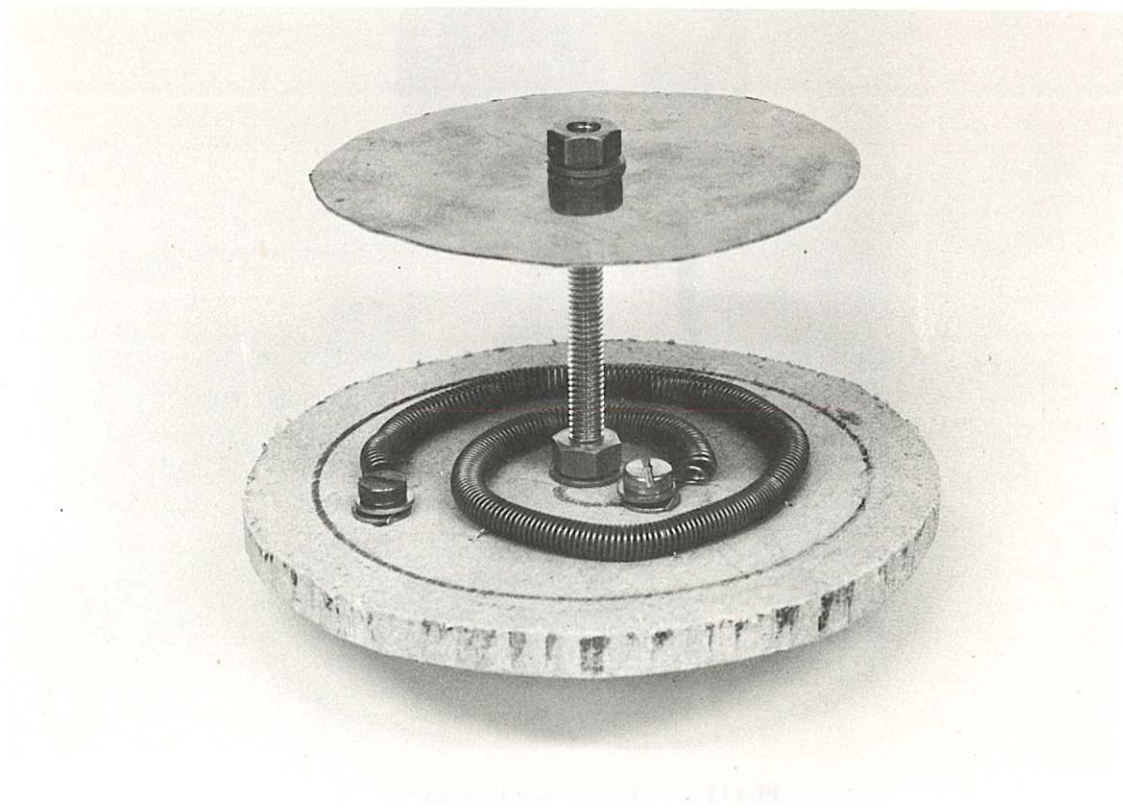


PLATE 2. The Heater Unit



PLATE 3. Assembly

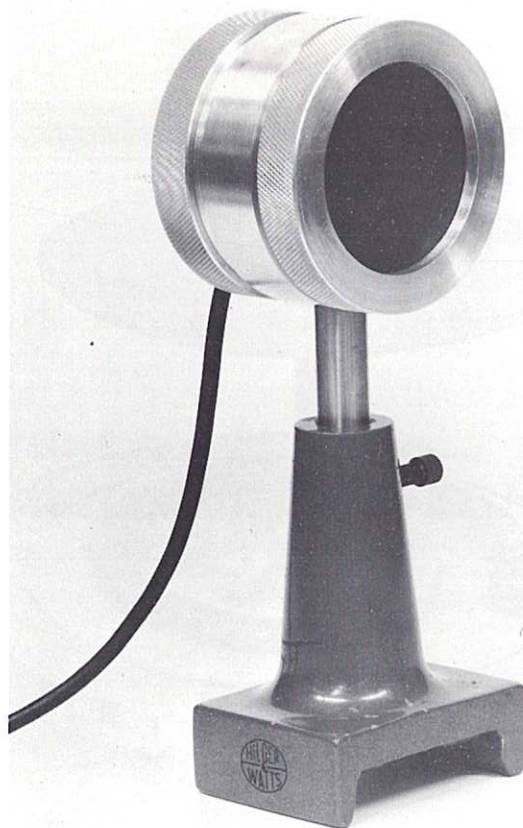


PLATE 4. The Finished Detector

PLATE 5. A CO₂ Laser Mode

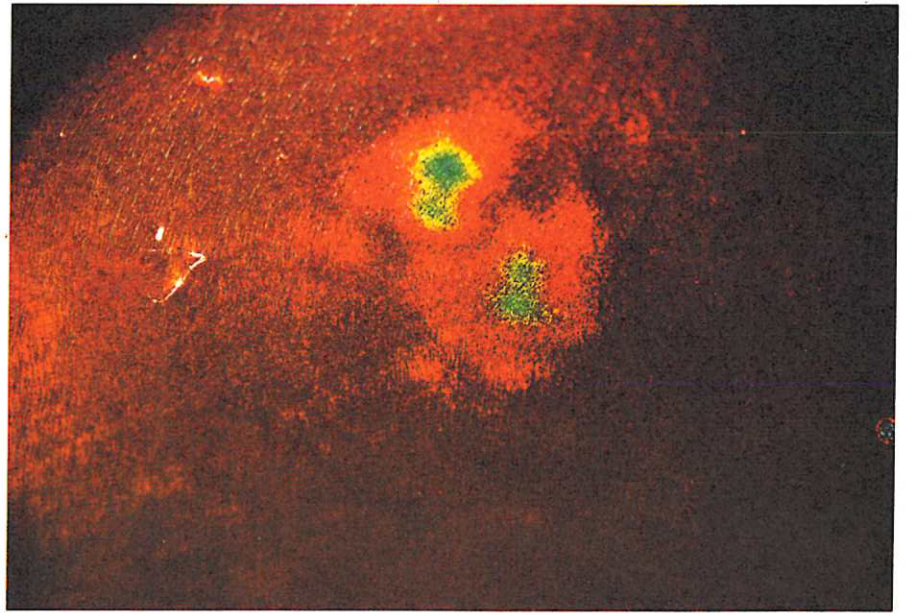


PLATE 6. Infra-Red Picture of Part of a Wire Gauze

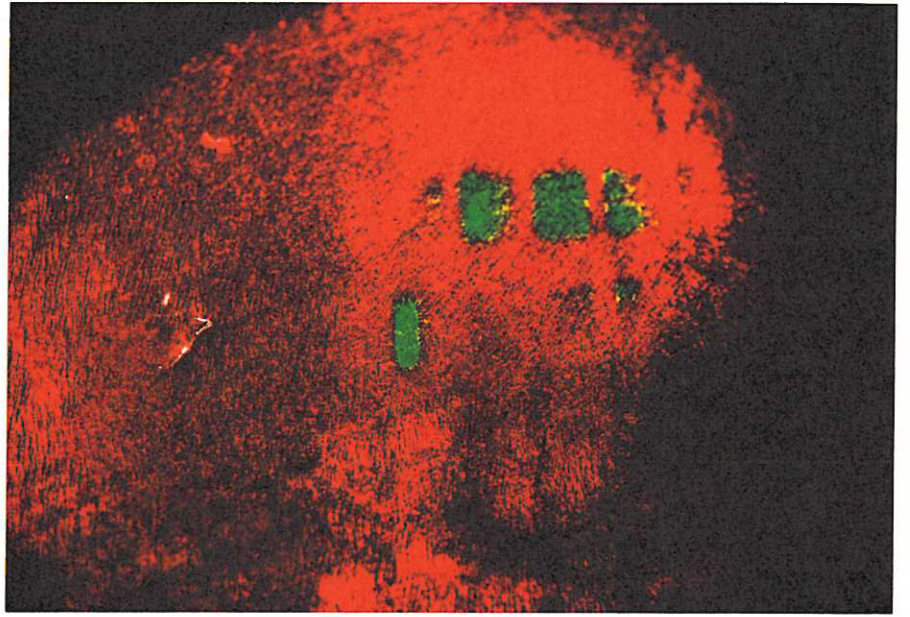
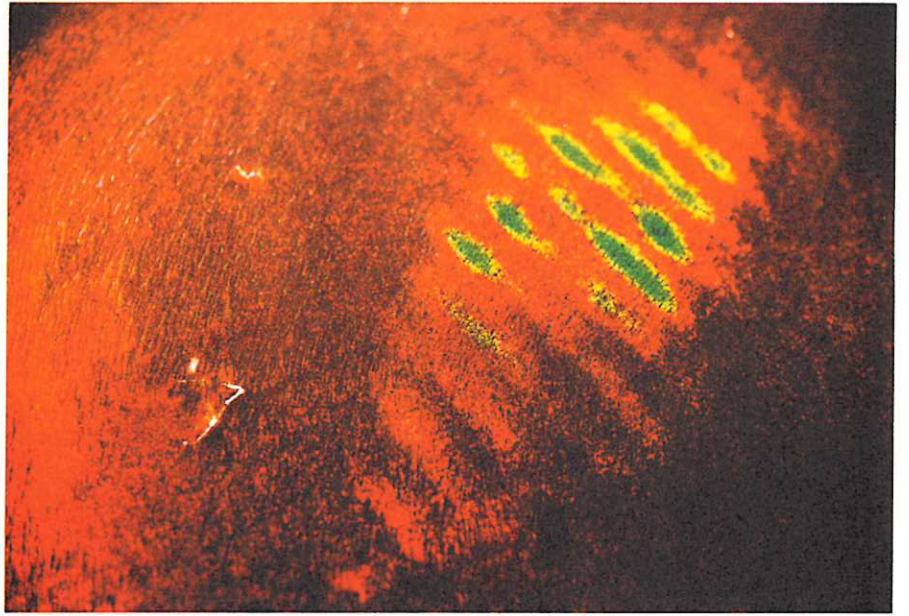


PLATE 7. Infra-Red Interference Pattern
Produced by a Germanium Wedge



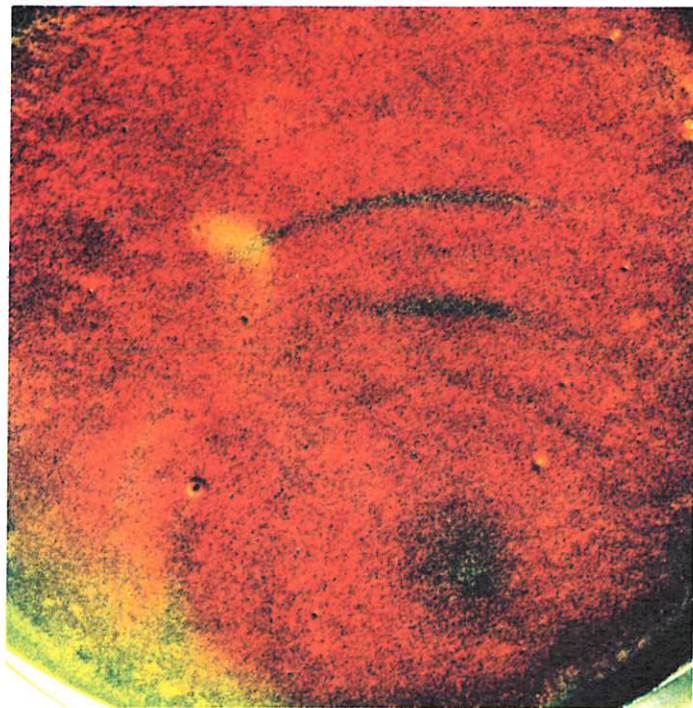
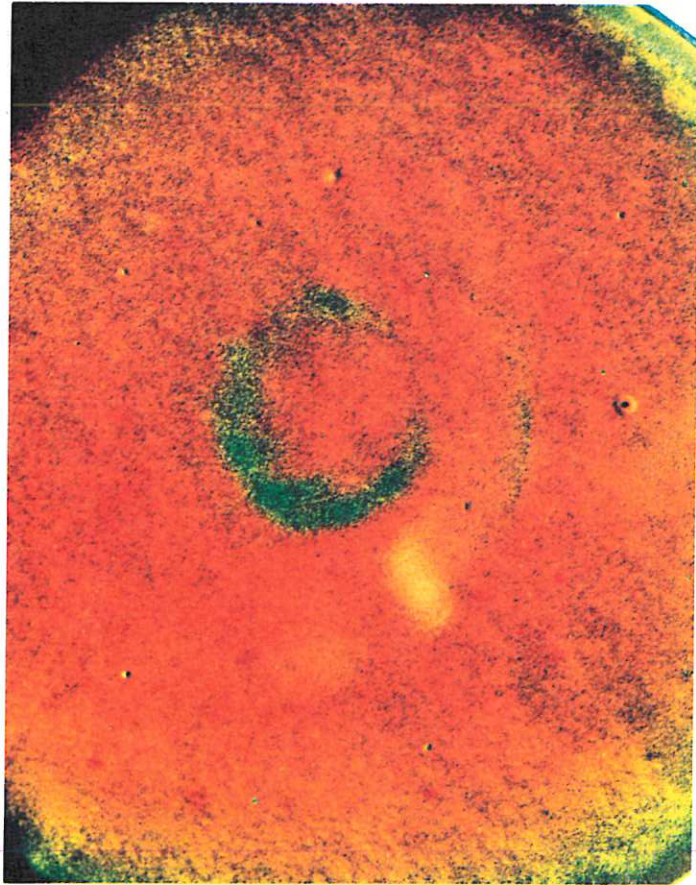


PLATE 8. Infra-Red Fabry-Perot Fringes
PLATE 9.



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