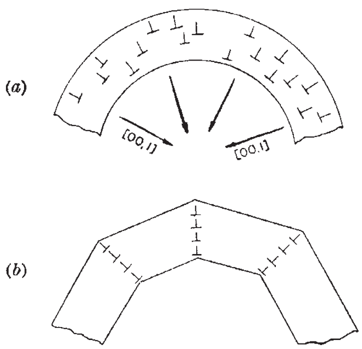

Fig. 4

in Fig. 4*b*, on a greatly exaggerated scale. From the degree of polygonization we estimate on the average an edge dislocation about every 200 atoms along the boundary.

We are indebted to Dr. W. W. Piper of this laboratory for making available to us these crystals, which he has grown by a vapour-phase technique, and to D. Hallgren for assistance in the measurements.

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A New Method of transporting Optical Images without Aberrations

The transportation of optical images has been carried out hitherto with the aid of lenses or mirrors or both. As with all optical systems, aberrations are introduced and the parts have to be aligned carefully; it seemed worth while, therefore, to search for a method by which no aberrations are introduced and which allows (strong) deviations from alignment without deterioration of the image. Consideration of the construction of the eye of some insects suggested another approach. If a bundle or sheaf of thin transparent fibres is cut off perpendicularly at both ends and an optical image is formed on one end, it will be seen at the other end, as the light entering one fibre can only leave this at the other end, provided leakage of light from one fibre to another of the bundle is prevented. Moreover, the cylindrical wall of each fibre must reflect the light as nearly completely as possible, because of the very numerous reflexions occurring when the fibres are thin compared to their length. Preliminary experiments, started in January 1950, have shown that coating the fibres with silver or any other metal yields an unsatisfactory transmission. A much better result was obtained when the fibres were coated with a layer of lower refractive index, which ensured total reflexion. This coating was isolated from the neighbouring fibres by a thin coat of black paint. In this way, flexible 'image rods' have been obtained with satisfactory transmission, a very good contrast in the end image, and with the possibility of using forms bent in any direction (up to at least 360°).

The first models were made of glass fibres. Much better transmission was obtained by means of plastic fibres, coated with either plastic of low refractive index or other transparent material of low refractive index. With an index of 1·52 for the core and 1·47 for the coating, the effective angular aperture of the light pencils entering and leaving the 'image rod' appeared to be about 1 : 1·8, which is ample for most practical applications, though a smaller difference of refractive indices would have been sufficient theoretically. Transmission, of course, is highly dependent on the transparency of the material used.

In order to obtain a high resolving power, the diameter of the fibres (or tubes) must be small. It appeared practicable to go down to 0·1 mm. for the core, though it seems possible to utilize smaller diameters. With the smaller diameters diffraction will play a preponderant part, and the fibres are then 'wave guides' for visible light. Of course, resolving power and overall transmission are reduced by the thickness of the coatings. The low-index coating must have at least a thickness of three to five times the wave-length. The length of the samples prepared in this laboratory varies from 6 to 20 cm.

Two obvious applications may be mentioned: cystoscopes and apparatus for the coding of two-dimensional pictures. Coding and decoding of two-dimensional pictures proved to be practicable.

The apparatus is different from the compound eye of an insect in that with the latter each 'fibre' has its own entrance lens, while with 'image rods' an image is formed on the entrance end by means of a system outside of the rod. Of course, entrance and exit surfaces of the rod may have another form than plane, for example, spherical.

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A Flexible Fibrescope, using Static Scanning

An optical unit has been devised which will convey optical images along a flexible axis. The unit comprises a bundle of fibres of glass, or other transparent material, and it therefore appears appropriate to introduce the term 'fibrescope' to denote it. An obvious use of the unit is to replace the train of lenses employed in conventional endoscopes. The existing instruments of this kind, for example, cystoscopes, gastroscopes and bronchoscopes, etc., consist of a train of copying lenses and intermediate field lenses. They are either rigid or have only limited flexibility. Moreover, the image quality of these systems is poor, since they consist only of positive lenses which give rise to a very large curvature of field. In existing gastroscopes the total number of lenses employed may be as many as fifty, and in consequence the light transmission is poor, due to the total glass path and the number of air–glass surfaces, in spite of blooming. Even more important in this respect, however, is the need to use small relative apertures for such instruments, this being necessary if acceptable definition is to be obtained with such large field curvature.

What was thought to be an entirely new approach to the problem of conveying images along a flexible axis was proposed by one of us (H. H. H.) as long

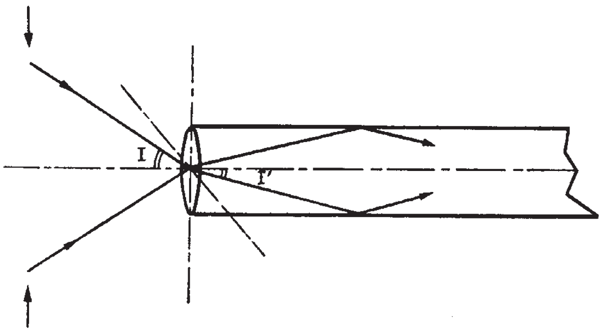

Fig. 1. Total reflexions in a single fibre

ago as 1949, although it was afterwards found that the idea had already been proposed by Baird in a British patent specification (1927 [1]). It is well known that light can be conducted along a curved glass rod due to multiple total internal reflexions at the walls of the rod. Very fine glass fibres should also possess this property and have the added advantage of flexibility. Theoretical considerations reveal that light should be safely conducted through a fibre of diameter 0·0005 in., below which diffraction effects become significant; the fibres act as wave guides, and energy escapes through the 'walls'[2]. The possibility of using fine fibres was experimentally verified by condensing light from a light source on one end of a fibre of borosilicate crown glass, 0·001 in. (= 0·025 mm.) in diameter and about 30 in. (= 750 mm.) long, and viewing the other end of the fibre with a low-power microscope.

It is easy to see by reference to Fig. 1 that the length of path along a multiply-reflected ray is simply equal to $L \sec I'$, where L is the axial length of the fibre and I' is the angle between the refracted ray in the fibre and the axis. Moreover, since the angle of incidence of this ray at the wall of the fibre is equal to $\frac{\pi}{2} - I'$, any ray which enters a fibre having a flat end will meet the walls of the fibre at less than critical incidence, providing the critical angle is greater than $\pi/4$. This requires that the index of refraction of the glass (μ) shall be greater than $\sqrt{2}$. The condition $\mu > 1{\cdot}41$ is satisfied by all the usual types of optical glass. Hence the loss of light along any ray occurs only because of absorption along a path of length $L \sec I'$. The transmission of the fibre T is therefore given by $\log_e T = -\alpha . L \sec I'$, where α is the absorption coefficient of glass.

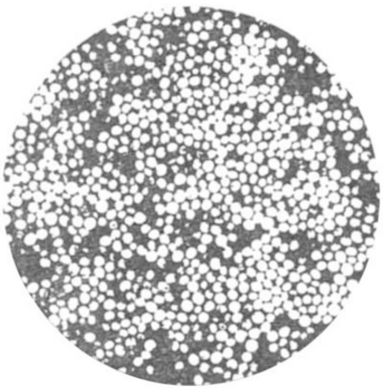

Fig. 2. Showing optical insulation of a roughly aligned fibrescope. × 50

The number of reflexions occurring in a length L is $\frac{L \tan I'}{D}$. For a ray at $I = 10°$ the number of reflexions in a fibre with $\mu = 1{\cdot}50$ and 0·001 in. diameter is 116 per in. of length. It is therefore essential that the surfaces of the fibre be very clean to avoid light being lost at each of these reflexions.

Having established that light could be guided along fine glass fibres with relatively small transmission losses, it was proposed in the new image conveyor to use a large number of regularly packed fibres, each of which could convey light from one element of the image formed on it to the other end of the bundle. This is a principle which we propose to call 'static scanning' in contrast to ordinary (dynamic) scanning of optical images. The success of 'static scanning' depends in practice on the optical insulation of each separate fibre being unaffected by the presence of other fibres close by it. Some preliminary experiments used a stack of a few hundred glass rods 1 mm. diameter and 25 in. long, and a roughly aligned stack of 0·001 in. diameter fibres also gave positive results, as may be seen in Fig. 2. Steps were then taken to construct a machine for making the first fibrescope unit.

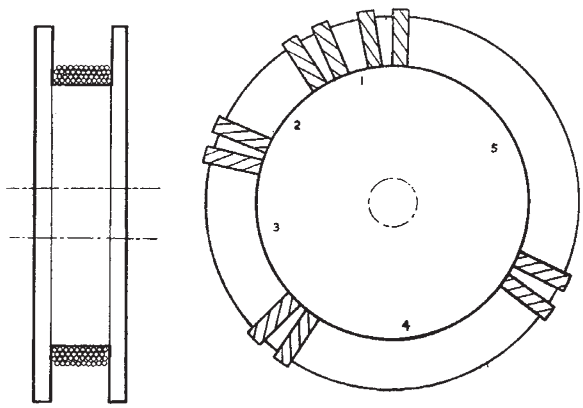

Fig. 3. Circular former used for aligning fibres

The method used for alignment depends on the availability of nominally infinite lengths of fibres of constant diameter of some optically transparent and homogeneous material. Very fine fibres are being made of material such as glass, quartz, nylons and polystyrene. However, of these, glass fibres seem to be the only ones which satisfy most of the requirements and are easily procurable. Glass fibres are preferred also because of their greater tensile strength as compared with that to be expected from the bulk material.

Long lengths of glass fibre were uniformly wound on a former having a peripheral groove of square cross-section, layer by layer, so that the nth layer was led to lie in the V grooves made by the $(n-1)$th layer. This is necessary to get close packing of the fibres, which is required both for mechanical stability and for obtaining the best resolving power. After winding the required number of layers, the bundle was gripped at different points by means of mechanical clamps (see Fig. 3), which were integral parts of the circular former. After tightening the clamps, the former itself was made to collapse so that the fibre stack slipped off the base, being held in position only by the clamps to yield different lengths of well-

Fig. 4. Fibrescope image of a simple test object. × 2

aligned fibres, as indicated by the numbers 1–5 around the periphery in Fig. 3. These numbers indicate the approximate length in inches of the lengths of fibres between successive cutting points. They make possible the production of a whole variety of lengths.

The former actually employed has a diameter of 5 in. with a groove of 0·25 in. square cross-section, and fibres of 0·0025 in. in diameter were wound on it. A 4-in. length of this bundle was used for testing the accuracy of alignment by passing a sharp image of a knife edge over one face of the bundle. The scanned image of the knife edge at the other end of the fibrescope showed no evidence of discontinuities arising from misalignment of the component fibres.

Light falling on any one fibre is distributed uniformly over the end face of the fibre on emergence. Moreover, if the image of a straight edge is formed on the object face of the fibrescope, the boundary of the edge will not generally lie across a single row of fibres the centres of which are in a straight line. In consequence, the image of the straight edge will be 'broken', but the discontinuity will never extend more than one fibre diameter into the dark portion of the image. Hence the size of detectable details should be of the order of twice the fibre diameter. In the present case, therefore, detail of 0·005 in. in size should be seen. This corresponds to a resolving power of 100 lines per in. on a line test chart. Tests were carried out on a 4-in. length of fibrescope from the above-mentioned bundle, and the theoretically expected resolving power of 100 lines to the inch was easily obtained.

The fibrescope was found to be robust, and a bending radius of less than 2 in. was easily achieved with the 4-in. length used, without any deterioration in the image quality. Fig. 4 shows a × 2 enlargement of the fibrescope image of a test object, the fibrescope having been curved into a quadrantal arc of a circle. Visually the image appeared to be of good contrast and well defined. Furthermore, up and down movement of the middle part of the fibre bundle by as much as 1 cm., the two ends remaining fixed, has no visible effect on the image quality.

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Nov. 22.

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[2] Schriever, O., *Ann. Phys.*, **63**, 645 (1920).

Application of the Hall Effect in a Semi-conductor to the Measurement of Power in an Electromagnetic Field

It is well known that if, in a piece of semi-conductor such as germanium or silicon, a magnetic field is set up along the z-axis, as defined by a Cartesian co-ordinate system, with current flow at right angles along the y-axis, then an electromotive force appears, due to the Hall effect[1] along the x-axis. This electromotive force at any instant is given by:

$$v = \left(\frac{R}{t}\right) I_c B \text{ volts,} \tag{1}$$

where B is instantaneous flux density in gauss; I_c is instantaneous current in amperes; R is Hall coefficient in volt. cm. per ampere gauss (for 'n' type germanium R has a value of about 8×10^{-5}); and t is thickness in cm. along the z-axis of the sample of material exhibiting the Hall effect. The particular virtue of a semi-conductor like germanium or silicon for this purpose is that it possesses a comparatively large Hall coefficient and allows a substantial penetration of the field into the material even at ultra-high frequencies.

The power density, p, at any instant in an electromagnetic field, measured in watts per sq. cm. of cross-sectional area of the field, is given by:

$$p = EH \text{ watts per sq. cm.,} \tag{2}$$

where E is instantaneous value in volts per cm. of the transverse component of the electric field; and H is instantaneous value in amperes per cm. of the transverse component of the magnetic field.

If, therefore, we arrange to produce through a piece of semi-conductor, placed in an electromagnetic field, a current I_c arising from the electric field E, then supposing in the first place we have a pure resistance circuit, the current I_c will be in phase with E and proportional to it. The magnetic flux density is $B = \mu H$, and if μ, the permeability of the medium, is constant, the Hall electromotive force will be a direct measure of the density of the power at any given point in the field. It is clear that the expressions (1) and (2) for the Hall electromotive force and the density of the power respectively are, apart from a constant term, exactly equivalent when, for example, I_c corresponds with E and B corresponds with H.

If for an alternating electromagnetic field the modulus of I_c is made proportional to the modulus of E, and the modulus of B proportional to the modulus of H, with the same phase difference between I_c and E as between B and H, then p is still obtained directly in terms of v. The total power can either be related to the density of power over a small area of the field, or obtained by integration.

The orthogonal spatial relationship which normally exists between the transverse components of E and H in an electromagnetic field enables these components to be used to produce the desired effect in the piece of semi-conductor, so that the Hall electromotive force then represents the longitudinal power.

The device is applicable to either steady, pulsating or alternating electromagnetic fields. When pulsating or alternating fields are used, it is necessary to obtain the true mean value in time of the Hall electromotive force taken over a complete period. Thus, represented as a function of time, the Hall electromotive force itself may be alternating or pulsating according to whether the electromagnetic field consists of, for example, a standing wave or a travelling wave; but in any event its true mean value over a complete