Measuring Systems and Transducers for Industrial Applications

Douglas F. Horne, M.B.E.

D.Sc., C.Eng., F.R.Ae.S., F.I.Prod.E.

Senior Lecturer, Cranfield Institute of Technology, 1971–81
Group Production Engineer, Rank Precision Industries Ltd
including Hilger and Watts Ltd, 1948–70

Adam Hilger, Bristol and Philadelphia

British Library Cataloguing in Publication Data

Horne, D. F.
Measuring systems and transducers for industrial applications.
1. Electronic measurements 2. Electronic instruments
I. Title
621.3815′48 TK7878.4

ISBN 0-85274-391-2

Library of Congress Cataloging-in-Publication Data

Horne, Douglas F. (Douglas Favel), 1915-
Measuring systems and transducers for industrial applications.

Bibliography: p.
Includes index.
1. Mensuration. 2. Transducers. I. Title.
T50.H64 1988 620′.0044 87-8865

ISBN 0-85274-391-2

Consultant editor: **Mr A. E. Bailey**

Published under the Adam Hilger imprint
by IOP Publishing Ltd
Techno House, Redcliffe Way, Bristol BS1 6NX
242 Cherry Street, Philadelphia, PA 19106, USA

Typeset by P&R Typesetters Ltd, Farnham, Surrey, UK
Printed in Great Britain by J W Arrowsmith, Ltd, Bristol

Measuring Systems and Transducers for Industrial Applications

By the same author

Optical Production Technology
Dividing, Ruling and Mask-making
Lens Mechanism Technology
Spectacle Lens Technology
Optical Instruments and their Applications
Photomasks, Scales and Gratings
Microcircuit Production Technology

To my wife

Author's Preface

Metrology, the science of measurement, is the foundation of industrial technology. Instruments are used for measuring geometrical quantities such as lengths, angles, shape, thickness, roundness, roughness, flatness or position and include the determination of radiation, luminance, colour, moisture content, pollution and many other properties that can be measured quantitatively.

The chapters in this book are complementary to those in *Optical Instruments and their Applications* (Adam Hilger, 1980) and illustrate the use of instruments which, in their manufacture, sometimes depend on processes described in *Optical Production Technology*, 2nd Edition (Adam Hilger, 1983). The descriptions are concerned with the use of instruments and not so much with design details, basic scientific principles that can be obtained from theoretical textbooks, or comparisons between competitive equipment.

Industrial control systems outside the manufacturing and process industries are now using transducers and microcomputers originally developed for entirely different purposes. The subjects in any one chapter may be unrelated, except through the use of a particular technique, and descriptions depend on the availability of information from instrument manufacturers. It is impossible to forecast where a technique will be used in the future. Innovation is the life-blood of a modern economy.

Sensors serve many different purposes, but they usually transduce a physical signal such as pressure, strain, acceleration, flow, temperature or displacement into an electrical signal. Transducers can change a modulated electric current into another form of energy, such as acoustic or electromagnetic waves, and modulators vary amplitude, frequency or phase characteristics of the waves. Electronic, ultrasonic, infrared and microwave transducers are capable of high accuracy when used in measuring systems.

Accuracy is described as an agreement of the result of measurement with the true value of a quantity being measured, usually obtained by calibration against a standard, whereas precision is the repeatability and predictability of a process or series of measurements. The difference between the measured value and the true value is the error, which may be random or systematic. Random errors arise from changes in ambient temperature and pressure or variations in a workpiece, and can be detected by a repetition of the measuring operation.

Systematic errors are constant errors that are not detected by a repetition of measurements and are usually the result of departures from procedure or mistakes. The resolution of a system is the ability to reproduce points, lines or surfaces on an object as separate entities that can be measured.

The practice of science and engineering is rapidly changing, and the distinction between them is becoming less marked, with the increase in the rate of technological progress and the need for special instrumentation to assist in the search for higher performance and lower costs.

I hope that students at universities, institutes of technology and polytechnics will find the information in this book useful to their studies and that production engineers and manufacturing managers will be able to apply the technology to their own products.

Science teachers should find the applications particularly helpful in their teaching. Technical education within schools should start at an early stage, so that by the age of 18 all children who hope to have a higher education in physics, electronics or engineering will appreciate why technology is essential to a modern economy. The ability to program a computer must be related to computer-aided manufacture and a knowledge of applications in commerce and industry.

There are over 250 photographs and diagrams in this book to illustrate equipment and processes from nearly 50 companies in Great Britain, Europe, Japan and the USA. I wish to thank those who have provided me with this information; their names are listed below in order of appearance in the book.

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I hope that I have not made any technical errors or significant omissions in the text but, if I have, I would like to be advised so that corrections can be made in future editions. Any opinions expressed are, of course, my responsibility and do not represent the policy of any company that has given information to me.

I wish to thank my wife for typing this manuscript and also the staff of Adam Hilger for the care they have taken whilst editing this book.

June 1987 **D F Horne**

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1 Optical and Infrared Transmitting Systems

1.1 Introduction

Thermal imaging enables us to see clearly in mist, smoke or dark-night conditions when conventional television cameras or visual telescopes cannot be used. At middle infrared wavelengths 3–5 μm and 8–14 μm there are two windows in the electromagnetic spectrum of the atmosphere where absorption by water vapour, carbon dioxide and ozone is low and transmission is possible over long distances (Fig. 1.1.1).

Electromagnetic radiation is emitted by all objects at a temperature above absolute zero (0 K or -273 °C) so that furniture, people and vehicles are all emitting radiation at varying wavelengths and intensities. A thermal imager can show heat escaping a badly insulated building or allow doctors to detect and diagnose diseases that cause unusual heat patterns in the body. The 8–14 μm window contains the wavelengths of peak emission from objects that are at normal outdoor temperatures. Silica glass does not transmit radiation beyond 2 μm wavelength and so, for the 8–12 μm range, the lenses are usually made of germanium (see § 1.5).

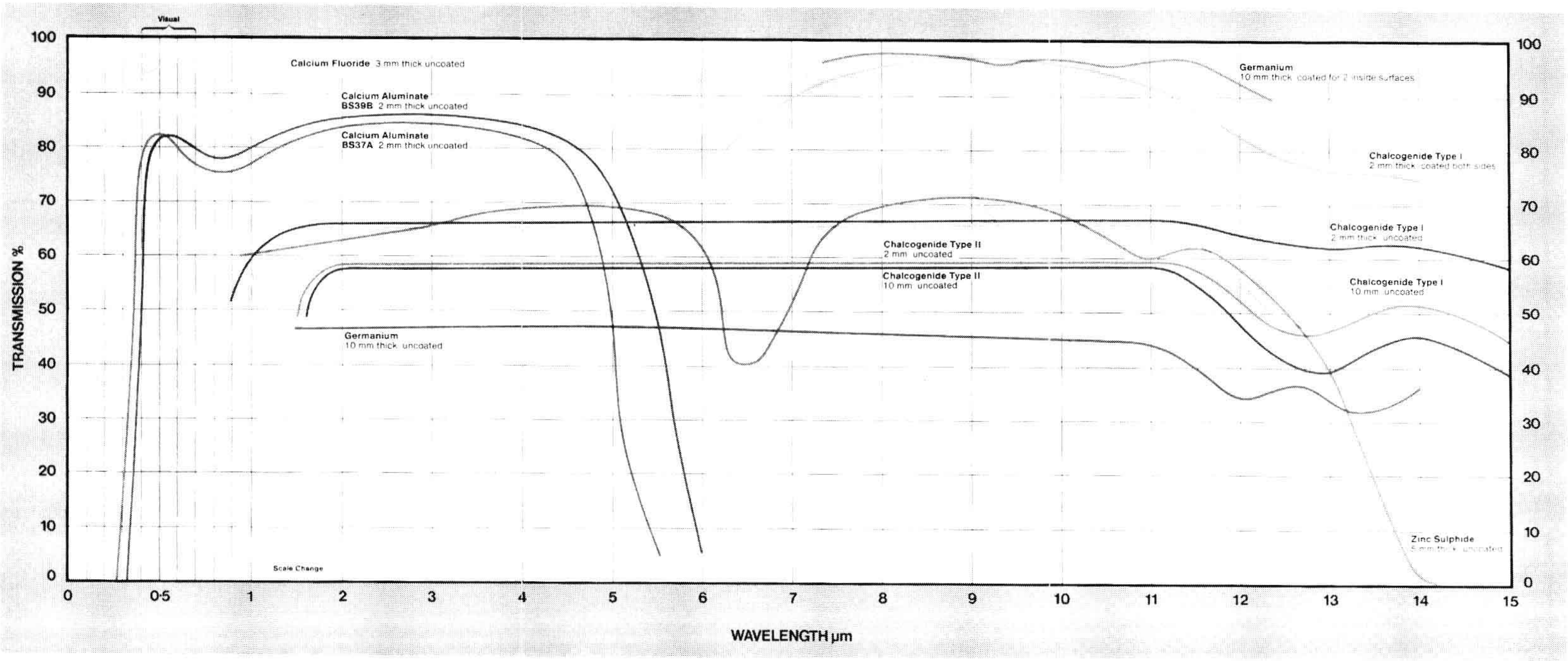
The 3–5 μm transmission range of optical components are made from materials such as the chalcogenide arsenic triselenide or arsenic trisulphide glasses, zinc selenide or silicon. Chalcogenide is a material generally used, in combination with germanium, to achromatise middle infrared optical systems and reduce aberrations (Fig. 1.1.2).

Silicate-based glasses have been used for the visible 0.4–0.7 μm wavelengths, and near-infrared 0.7–2.0 μm wavelengths, for many types of optical component including incoherent and coherent fibre optic bundles. Incoherent bundles are primarily used for light guides and illumination systems but coherent bundles, faceplates and windows will transfer clear images provided that the thousands of fibres are in the same relative position at each end of the bundle. Each fibre carries one element of light and so definition and contrast depend upon the cross sectional size of the elements (Fig. 1.1.3).

Telecommunications and data links

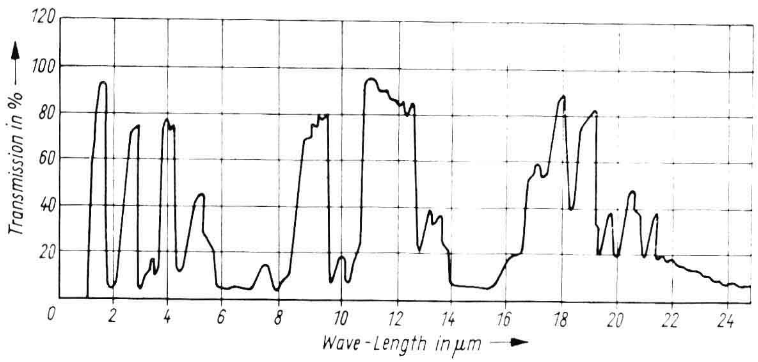
In telecommunications systems, fused silica fibres, doped with germanium, have great information-carrying capacity at near-infrared wavelengths, with immunity to cross-talk and freedom from electromagnetic interference. These fibres are replacing conventional copper-wire systems for long-distance or high-data-rate transmissions. Compared with metallic cable systems, optical fibres are low in transmission loss, quartz is a viable alternative raw material in view of dwindling copper supplies, and lightweight cables are possible since the specific weight of silica is less than 25 % that of copper.

Optical fibres are analogous to waveguides in microwave transmission systems. The light wave is refracted at the interface of two different

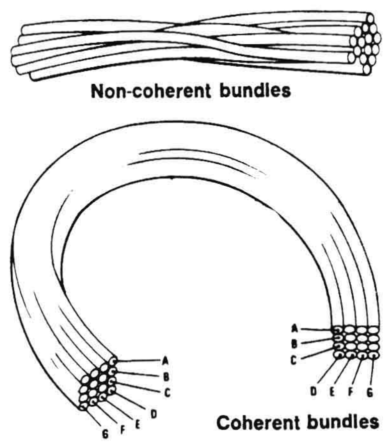


1.1.2
Transmission characteristics of infrared materials manufactured by Barr and Stroud Ltd.

1.1.1
Spectral transmission of the atmosphere.



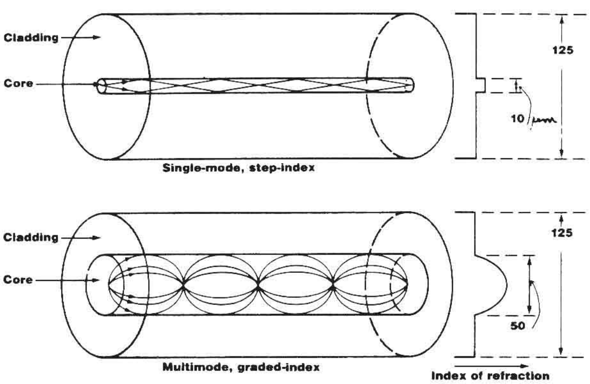
1.1.3
Flexible non-coherent and coherent fibre optic bundles.

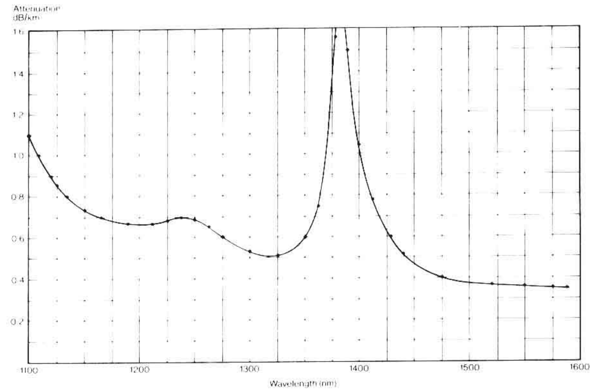


conducting transparent dielectric materials, and at the critical angle of incidence, refraction becomes reflection. The non-axial waves or modes are identified as a function of their entry angle. Waves at small angles are called low order and those launched at large angles are high order. The fibre optic core has a high refractive index and the cladding a low refractive index. Light passes down the core by means of a series of total internal reflections. Step-index fibres typically with a core diameter of 50 μm and a cladding diameter of 125 μm, which can be used for illumination and imaging, are unsuitable for telecommunications because of different propagation paths within the fibres. Rays launched at different angles arrive at the end of a fibre at varying times and so binary signals are destroyed. Graded-index cores made from lead silicate glass counteract the inequality in path length by having a controlled refractive index profile, and so multimode fibres are used for data transmission over distances of up to about 500 m length (Fig. 1.1.4).

If the size of the core diameter is reduced to a few times the wavelength of radiation to be transmitted, only one mode can propagate and this travels directly down the centre of a fibre. The switch from multimode to monomode propagation occurs at the cut-off wavelength and the first generation of single-mode fibres, based on doped silica glass and an 8 μm core with

1.1.4
Single-mode step-index fibres are used for long-distance telecommunication systems. Multimode graded-index cores are larger, permitting the optical path to zigzag within a refractive index profile which is close to a parabola, and are used for shorter data transmission systems. The measurements are in μm.





1.1.5
Typical spectral attenuation of single-mode silica glass fibre.

125 μm diameter cladding, has an optimum transmission bandwidth at 1.3 μm wavelength. Since attenuation is only 0.5 dB km^{-1} the fibre is capable of distances over 30 km, and possibly as great as 200 km, between repeater spacings (Fig. 1.1.5).

Doped fused silica fibres in single mode can be made to transmit at 1.55 μm wavelength, with a loss of about 0.2 dB km^{-1}, but if lower losses are necessary then better materials must be developed. Middle-infrared transmitting glasses will become the next generation of optical communication fibres since they can improve on the intrinsic losses in silica-based glasses.

There are two characteristics that determine loss limits of a material, namely Rayleigh scattering and absorption. Scattering is proportional to the reciprocal of the wavelength to the fourth power, and so doubling the operating wavelength will decrease the intrinsic scattering by a factor of 16. On the other hand, absorption loss increases rapidly as the wavelength increases. Hence, because scattering and absorption have an opposite dependence, there is an optimum transmitting wavelength for each particular material.

Potentially useful materials for telecommunications and sensors are based on chalcogenide glasses, halides such as beryllium fluoride, or heavy-metal oxides. Experiments have produced fibres from mixtures of ZrF_4, BaF_2, NaF, LaF_3 and AlF_3 for the core and the same mixture with hafnium fluoride (HfF_4) in the cladding. Heavy-metal fluoride glass fibres may have losses of only 0.1–0.001 dB km^{-1} at 2–4 μm wavelengths

Graded-index optical components

Graded-index cores are used in multimode fibres, but the possibility of a continuous variation of refractive index in lens systems will eliminate many design constraints, and require fewer elements of simpler shape, than when homogeneous components are used.

By exchanging dopant ions in a molten salt bath the graded-index treatment has a similarity to the chemical strengthening of ophthalmic lenses, when there is an exchange of sodium ions in the glass for potassium ions from molten potassium nitrate. Refractive index gradients in lenses are made by exchanging sodium or potassium ions in the glass for lithium, caesium, thallium or silver ions. Ordinary borosilicate glasses require a long diffusion time because of the tightly bound ions in the structure, so less dense porous glasses are needed to accept the dopants in a shorter time. Porous glasses may be produced by dissolving out or leaching molecules from the glass to leave holes into which modifiers can be introduced by a diffusion process.

Infrared materials such as germanium, silicon, zinc selenide and zinc sulphide can also be treated to provide a graded refractive index.

Graded-index designs require fewer and simpler elements because, instead of refracting light at the surface of a homogeneous lens, the light bends continuously throughout each element thickness and the rays form a curvilinear instead of a rectilinear path. Refraction depends on the lens thickness as well as the surface curvature. By spherical grinding and polishing a lens, after treatment for an index gradient, it is possible to arrange for the refractive index at an edge to be lower than that at the centre. This axial gradient produces the equivalent of an aspheric surface without the need to generate expensive non-spherical surfaces for the correction of spherical aberrations.

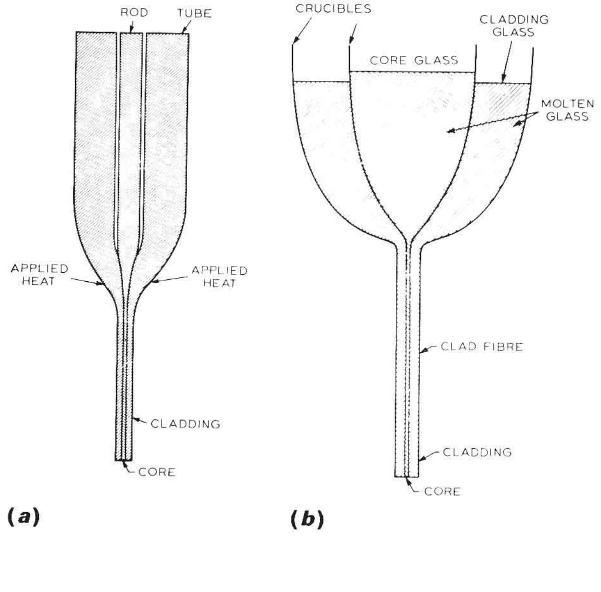
1.2 Optical fibres and semiconductor devices

Production of silica glass fibres

Most low-loss optical fibres for the near infrared are at present made from silica glass, and there are several methods for making and pulling the fibres. The preform rod-in-the-tube method uses a fire-polished rod, made of glass about 7–10 mm in diameter and at least 1 m long with the desired core refractive index, inserted in a tube made of pure silica low-index glass for the cladding. For graded-index cores the refractive index drops from a maximum at the axis to a low value at the cladding in an approximately parabolic fashion by means of various layers of differently doped glass (Fig. 1.2.1).

A production method for making 'state-of-the-art' optical fibre preform cores by modified chemical vapour deposition (MCVD) is based on a quartz or silica glass tube which is rotated in a lathe whilst reactants such as $SiCl_4$ and dopants $GeCl_4$, BBr_3 or $POCl_3$ are passed through it. An oxy-hydrogen flame burner traverses the tube and applies local heat to about 2000 °C so that the reactants in the tube oxidise to form a doped silica soot which adheres to the inner wall in glassy layers. The reactant flow is changed to control the composition of about 45 glass layers and then, at a temperature of around 2200 °C,

1.2.1
(*a*) Preform rod-in-tube method for fibre pulling.
(*b*) Double-crucible method for fibre pulling.

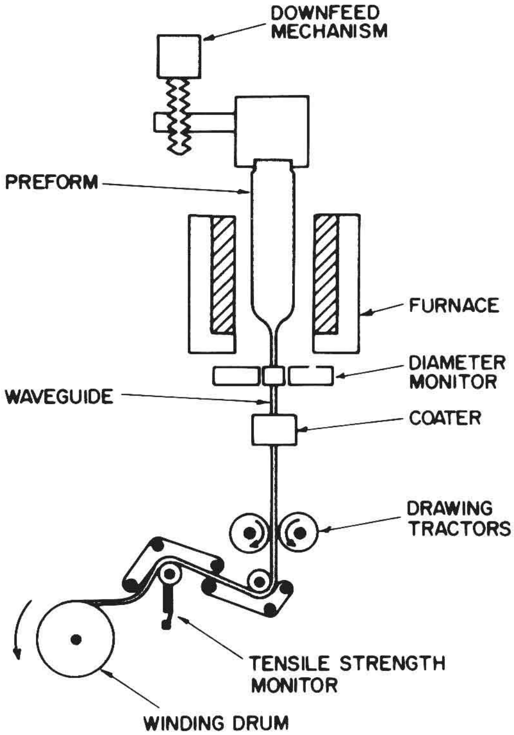


(*a*) **(*b*)**

the tube is collapsed into a solid preform before fibre-drawing in a low-index glass cladding.

Preform cores in tubes are placed in a high-temperature graphite resistance or zirconia induction furnace and drawn into a fibre until the outer cladding is about 125 μm in diameter. The core and cladding glasses maintain their geometrical relationships, although the reduction in diameter may be as high as 300:1. A gauge monitors the diameter of the fibre before it is coated by a layer of ultraviolet-curable acrylate or aluminium material. Coatings are necessary to provide a high intrinsic strength, seal the fibre against moisture penetration and facilitate handling of the material during cable production (see §§2.8 and 6.2).

In the double-crucible method molten borosilicate glass produced from silica, sodium tetraborate and sodium carbonate powders is held in two concentric crucibles. The inner crucible, containing the high-index core material, is made from platinum, and glass for low-index cladding is contained in the outer crucible. Since both are concentric to each other the glasses flow out to form a clad fibre. Single-mode fibres can be made with a very narrow core and a relatively thick cladding (Fig. 1.2.2).



1.2.2
Schematic of fibre-pulling equipment.

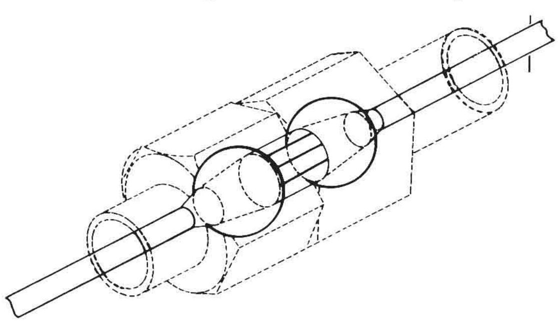
Optical fibre connectors

Attenuation in a fibre optic cable includes some loss at the entrance and exit which is minimal when the fibre ends are smooth and square. Any radial, angular or longitudinal fibre misalignment at connectors contributes to the escape of light and signal power loss. Single-mode fibres, typically with 8–10 μm core diameters, require concentric connectors for fibre-to-fibre, laser diode and detector joints. The precision polishing of fibre ends is a problem to be avoided if at all possible.

Butt-type connectors are not suitable for single-mode fibres because of the need for extremely accurate alignment; also, the core cannot be assumed to be exactly in the geometric centre of a fibre because of small movements of the core in the cladding during manufacture. Small polished glass spheres, with refractive index ranges from 1.5 to 1.9, can increase the efficiency of both multimode and single-mode connectors. Light from a fibre end is collected by one sphere, for focusing on the adjoining fibre with an acceptable loss at the joint of 0.7–1.5 dB (Fig. 1.2.3).

Sometimes a lens is needed at the end of a fibre and, instead of using a separate lens, the heat from an electric arc in a fusion splicer can be used to form, by surface tension, a spherical shape on the fibre end. Single-mode fibre ends are more difficult to form by fusion because of their very small diameter and so a tapered cone

1.2.3
Glass spheres mounted in a monomode connector, with collimated light between the two spheres.



can be etched, with hydrofluoric acid, to form a radius of curvature equal to half the core diameter.

Light-emitting diodes, injection laser diodes and photodiode detectors

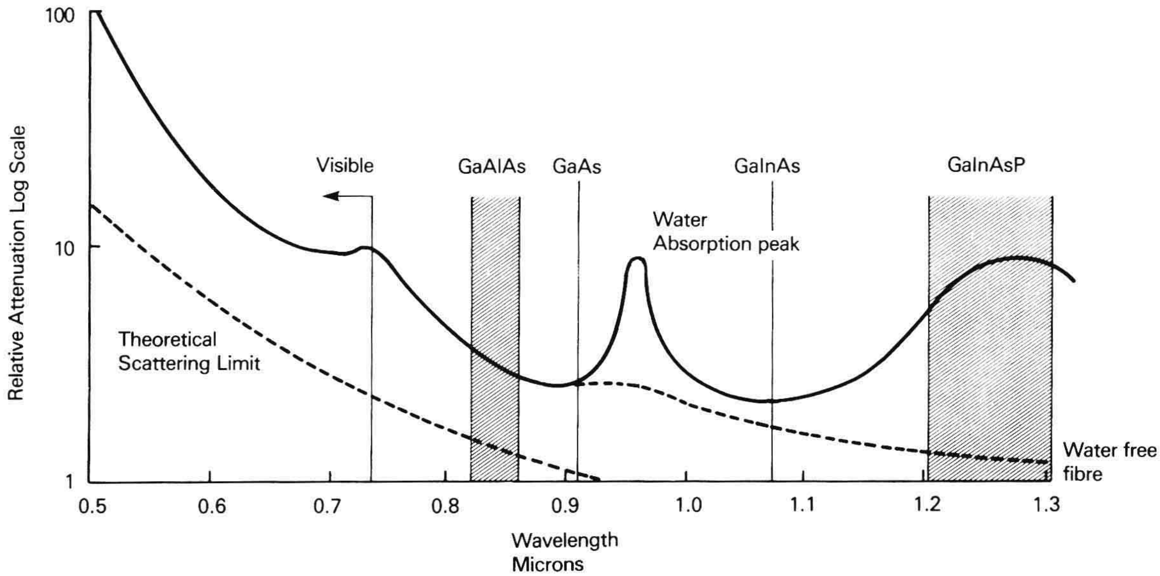
Light-emitting diodes and semiconductor diode lasers all use a p–n junction in a semiconductor to convert an applied electrical signal to electromagnetic radiation in the visible or near-infrared spectrum. The decision on which device is most suitable for a particular transmission must take into account the receiver sensitivity and losses from the fibres and connectors, as well as cost of the pair of transmitter–receivers.

Transmitters are needed for input into optical fibres, and receivers accept the output. System losses must be related to output characteristics of the light source. The term 'transmitter' refers to the combination of light source and driver circuitry that is used for modulation. At the output end of a fibre the term 'receiver' refers to a light-detecting transducer and its related electronics for restoration of the original input signal and the desired amplification. Emitters include light-emitting diodes (LED) and injection laser diodes (ILD). Infrared emitted from ILD is nearly monochromatic at about 900 nm wavelength and, with their high power, laser sources are very suitable for transmission applications involving long distances and wide bandwidths.

Light-emitting diodes vary in wavelength from 565 nm (green) to 1300 nm (infrared) with 850 nm (infrared) emitting within one of the lowest attenuation windows for silica glass fibres. The LED satisfies the requirements for most data links where rates are under 10 MHz and distances less than 1 km. Pigtailed and ferruled emitters include a length of optical fibre so that the emitter-to-fibre interface is made during manufacture and the user only has to make the fibre-to-fibre coupling by fusion splicing or with an epoxy technique (Fig. 1.2.4).

At the receiving end of a fibre optic data link a photodetector senses light and demodulates it by generating an electric current proportional to the intensity of the radiation. There are several types of photodiode or phototransistor that can be used as detectors, but PIN photodiodes are usually chosen for data transmission since they are relatively inexpensive and easy to use. The performance of a PIN photodiode is improved by an undoped intrinsic layer that lowers the capacitance and permits a good frequency response. The spectral response of photodiode is directly proportional to the material composition of the light-absorbing region, and a GaAs PIN photo-

1.2.4
Light-emitting diodes and attenuation on a water-free silica fibre.



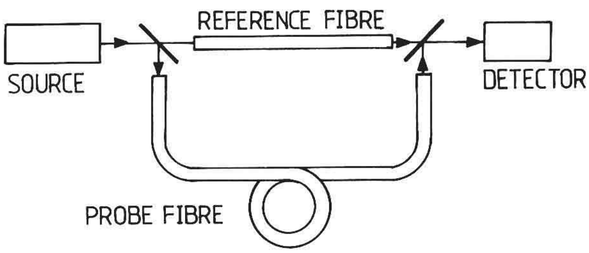
diode has a useful detection range of 750–900 nm wavelength. For the wavelength range 1300–1600 nm a GaAs/InP system can be fabricated.

There are a variety of applications for fibre optics as sensors such as (*a*) the measurement of a force by the slight stretching of a fibre, (*b*) the monitoring of liquid levels by the loss of total internal reflection when a liquid is in contact with a prism at the end of a fibre or (*c*) the detection of the presence of methane in a coal mine. Methane absorbs light strongly at 1.65 μm wavelength and so, by using a suitable GaAs–InAs laser diode and optical fibres, if a beam of light in an air gap becomes infiltrated with methane the light will be cut off from a detector and operate an alarm. This system can be applied to many industrial gases.

Single-polarisation fibre sensors

A ray of light passing down a single-mode fibre has two propagation modes with perpendicular electromagnetic polarisation planes. These modes are very similar and can be transferred to each other by a disturbance in the fibre such as a bend, change of temperature or imperfection in the fibre material. These polarisation modes do not affect signals for telecommunications, but there are some applications in which a single polarisation plane is essential. One way to maintain the same polarisation in a fibre is to introduce asymmetry into the fibre structure. If only one polarisation mode enters an asymmetric fibre the output radiation should be linearly polarised. Amongst the variety of core cross sections that are possible, known as geometrical birefringence fibres, non-symmetrical parts may be highly doped with a material such as boron. Single-polarisation fibres propagating only one polarisation mode that disable the other mode from transmitting are now being developed.

Major applications such as interferometric sensors and fibre optic gyroscopes require single-polarisation characteristics and asymmetry, without cross-talk, over long lengths of fibre. The fibre optic interferometric sensor uses a laser beam divided into two single-mode fibres, one for a probe and the other for the reference, so that the probe fibre is exposed to the strain to be measured such as temperature, pressure or acoustic waves. The reference fibre is isolated in a stable environment. The fibre length of the probe is altered by the force and so the transit time of light in the fibre varies; this alters its phase relationship with the reference fibre. This change in phase and interference of electromagnetic waves is extremely sensitive for small measurements (Fig. 1.2.5).



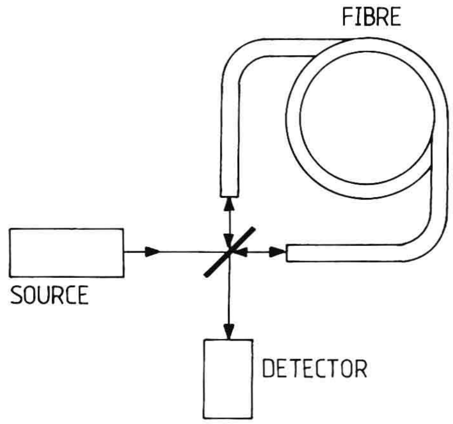
1.2.5
Fibre optic interferometric sensor.

Fibre optic gyroscopes

The fibre optic gyroscope, a version of the interferometric sensor, could supersede the ring-laser gyro or the mechanical spinning mass since there are no precision machined parts and the fibre optic system is not affected by vibration. Gyroscopes measure rotation, for vehicle navigation, but they can also be used for bore-hole drilling and platform stabilisation. Another application will be in the positioning of robot arms where an accurate response to rapid movements is very important.

Fibre optic gyros are capable of measuring high sustained rotation rates above 1000 $^\circ s^{-1}$ and also very small rotation rates less than 0.1 $^\circ h^{-1}$ in temperatures ranging from $-55\,^\circ$C to 85 $^\circ$C. The fibres used in this application have a high numerical aperture and are coated with flexible polymers so that they can be wound into small coils.

Two coherent beams of light from a laser diode are directed into the opposite ends of a coil of single-mode polarisation-maintaining fibre which is several hundred metres in length. The rays of light traverse the fibre in opposite directions and recombine at the interferometer. When the coil is stationary the opposed light paths will be the same length but if the coil is rotated there will be an optical path difference and the phase difference can be used to measure the rate of rotation (Fig. 1.2.6).



1.2.6
System diagram for fibre optic gyroscope in which hundreds of coils of monofibre are used as the sensor in conjunction with integrated optics on a single chip of lithium niobate.

Hybrid integrated optics, using a single chip of lithium niobate as the substrate, include beam splitters, polarisers and modulators which may be used in conjunction with single-polarisation fibres.

Flexible lasers

Conventional lasers are straight and rigid, with accurately positioned mirrors at each end, but the availability of single-mode single-polarisation flexible fibre eliminates the need for separate mirrors. The fibres, doped with rare-earth elements in the core, have transparent windows at certain wavelengths and the laser atoms have no contamination since they are enclosed in solid material which can be pumped longitudinally with high efficiency (see §2.1).

1.3 Fibre optic sensors

Fibre optic sensors are located at the monitoring position, which may be in a hazardous area, with the optical processor containing a pulsed xenon lamp and double beam detection system in a central control room. Optrodes are conventional fibres in lengths up to 15 m, for transmission at wavelengths between 270 and 720 nm, which have been packaged at the specimen end so that they can be immersed in liquids or used on measuring fixtures (Fig. 1.3.1)

The Oriel light source and detector system uses a 1 W, 9 Hz ultraviolet–visible xenon lamp, and measurements can be made in remote locations such as on robot arms, radioactive buildings, fermentation systems, high-voltage or explosive areas and in river or reservoir locations. Analytical measurements can be made in 2 μs and so freeze the motion of fast moving objects, such as choppers or rotors, for monitoring industrial processes (Fig. 1.3.2).

The analyser is a compact console in which the source and detector are linked to the sample by two light guides. A photodiode is located alongside the source to monitor pulse intensity from pulse to pulse. Intensity variations are measured and used to correct the main photomultiplier measurement. Optrodes can measure absorption or transmission of liquids by immersion of a probe into the sample. Light from one branch passes through the liquid and is reflected back, by a rear surface mirror, to be collected at the second branch, which takes the light to a photomultiplier for measurement.

If a liquid has an exceptionally high absorption then the sample must be evaluated by reflection measurements instead of by transmission through the sample. Optrodes for measurement of front surface reflection from solid surfaces are supplied with an adjustable end cap, to maintain the probe end at a constant distance, for reproducible comparative measurements. These sensors can be mounted on motorised X–Y scanners for automated surface scanning (see §5.5).