Optical Fiber Sensors

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PREFACE

This volume presents the proceedings of a summer course on "Optical Fiber Sensors", which was held from May 2 to 10, 1986, in Erice, Italy. This is the 11th in a series of courses conducted by the International School of Quantum Electronics, on behalf of the "Ettore Majorana" Center for Scientific Culture.

Although optical systems have long played an essential role in the fields of instrumentation and sensors, the development of optical fiber communications and related technologies has greatly enlarged the possibility for sensor systems. The successful applications of optical fibers have stimulated additional creative work in other guided-wave technologies, both in fibers and in the planar geometries characteristic of integrated optics.

Among this newer work, fiber optic and integrated optic sensors play a particularly promising role. The propagation of light in guided-wave structures is sensitive to a number of phenomena which can change the physical geometry or refractive properties of the material. By using ingenuity and good design to isolate the desired effects, researchers have been able to construct a variety of compact and useful sensor devices, as are described in these papers. In many cases, a sensitive optical device involving no electrical connections to the phenomena being sensed provides a unique and necessary non-interfering sensing technique.

The papers published here include discussions of the basic principles of optical fiber sensors and their major applications in measuring rotation, acoustic vibration, intensity, temperature, strain, and chemical concentration. In addition, there are discussions of integrated optic structures as applied to sensing, and of the engineering technologies underlying both fiber and integrated optic sensor devices.

This course was initiated at the suggestion of one of us and was greatly successful, bringing together a hundred people among the leading

researchers in this field coming from all over the world (16 NATO countries and 9 non NATO countries). We appreciate the hard work of the lecturers in providing their manuscripts for rapid publication.
Owing to their exceptional level a few papers have been also included from lecturers who had prepared their papers for presentation in Erice but at the last minute were unable to attend the course.

Due to the severe time requests we have been obliged to leave out the contributions of very busy authors (B.Crosignani, D.N.Payne, G.Tangonan). The level of the course has been so high that it might be considered more similar to a workshop than a summer school; accordingly contributed papers by attendees have been included in the proceedings. The articles in this volume have been judged and accepted on their scientific quality, and language corrections may have been sacrificed in order to allow quick dissemination of knowledge to prevail.

We would like to acknowledge with thanks the financial support for this course provided by NATO, the North Atlantic Treaty Organization , the Italian Ministry of Scientific and Technological Research, the Sicilian Regional Government and the National Research Council (C.N.R.). We also thank the U.S.National Science Foundation for providing travel grants for three graduate students to attend the course, and the U.S. Army Research Development and Standardization Group, U.K. We also welcome Martinus Nijhoff as the Publishers of our proceedings.

Finally, but most importantly, we are glad to take the opportunity to acknowledge the skillfull assistance of Mrs. Vanna Cammelli and Mrs. Mary Schram as regards both the course and its proceedings.

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MONOMODE FIBRE OPTIC INTERFEROMETERS AND THEIR APPLICATION IN SENSING SYSTEMS

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1. INTRODUCTION

In this chapter we review the Michelson, Mach Zehnder and Fabry-Perot interferometers and introduce their fibre optic equivalents, together with signal processing techniques which enable these devices to operate over a large dynamic range with constant sensitivity to induced optical phase changes. The lower resolution polarimetric (differential) interferometer and associated signal processing to enable it to be operated remotely is also considered. The application of these novel fibre optic interferometers to a variety of measurements such as temperature, magnetic field, displacement and sound waves is described.

2. OPTICAL INTERFEROMETRY

2.1. Introduction

In the laboratory, optical interferometers are mainly used either: (i) to determine the fundamental parameters of an optical source such as its wavelength or coherence length; or (ii) in high precision optical path difference (OPD) measurements, where the change in the OPD may occur because of a physical displacement, or a change in the optical constants of the light transporting medium (e.g. refractive index) in part of the interferometer.

Optical interferometer is a relatively old subject, and most of these classic instruments were introduced well over 70 years ago; indeed the first interferometers are associated with the founders of modern optics such as Newton, Young and Michelson.

Before discussing fibre optic interferometers, it is appropriate to summarise the basic operation of a conventional interferometer and to evaluate its potential as a general purpose displacement sensor. For simplicity we choose the Michelson two-beam interferometer shown in figure 1(a). Light from the optical source, ideally a single-frequency laser, is amplitude divided at the beam splitter to produce reference and signal beams which propagate in the arms of the interferometer. These beams may be represented by

$$\text{Reference} \equiv A_R \exp[i(\omega_L t + 2kx_R)] \tag{1.1}$$

$$\text{Signal} \equiv A_S \exp[i(\omega_L t + 2kx_S)] \tag{1.2}$$

A_R and A_S are the amplitudes of the reference and signal beams; x_R and x_S are the distances the light travels between the reference (M_R) and signal (M_S) mirrors respectively; $k = 2\pi n/\lambda$, the propagation constant, where λ is the vacuum wavelength of the light, n is the refractive index of the air path and ω_L is the angular frequency of the light source. After traversing the interferometer arms the beams coherently recombine at *the beam splitter. The current I_D of the photodetector used to record the* irradiance output of the interferometer is given by

$$I_D = \varepsilon(1 + K \cos \phi(t)) \quad (1.3)$$

$\phi(t)$, the time-dependent phase difference between the arms of the interferometer, is equal to $2k|x_S(t) - x_R|$ where $x_R \neq x_R(t)$, K is the fringe visibility and equals 1 when $A_R = A_S$ and ε is related to the input optical power. The transfer function of the interferometer, I_D, plotted as a function of ϕ is shown in figure 1(b), where we have assumed that it is operating with the following restrictions, which can be closely approxi-

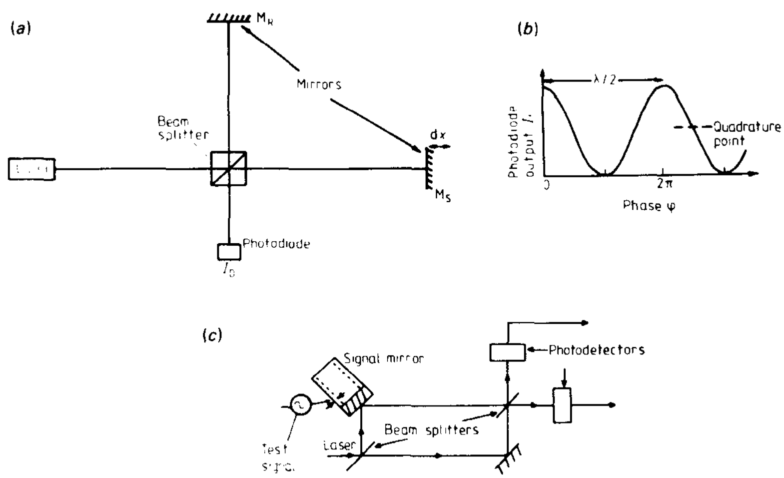

FIGURE 1. (a) Schematic diagram showing a conventional Michelson interferometer. (b) Michelson transfer function, photodiode current I_D as a function of the relative (static) phase ϕ. (c) Schematic diagram showing a conventional Mach-Zehnder interferometer.

mated to under normal laboratory conditions:

(i) $A_R = A_S$, i.e. the beams are of equal intensity and state of polarisation;

(ii) the bandwidth of the optical source is extremely narrow;

(iii) the absolute optical frequency of the source is constant;

(iv) the optical alignment is 'perfect' and stable.

Under these operating conditions it is possible to detect extremely small changes in the OPD of the interferometer, for example Moss et al (1971) have determined periodic displacement amplitudes of the order of 10^{-14} m. The ultimate limit of detectability is defined by a signal-to-noise ratio of unity, the so called 'shot-noise' limit (set by the photodetector); this concept is discussed in §6.2.1.

It is evident that the performance of many primary sensors based upon a measurand-induced dimensional change could be significantly improved if it were possible to use interferometric techniques. Although interferometers offer tremendous resolution (or sensitivity), it is only very recently that any significant effort has been devoted to developing them into general purpose displacement sensors. This is primarily because their operation is dependent on the relative alignment of: (i) the internal optical beams and (ii) the input light beam with the interferometer itself. In a typical instrument where conventional beam splitters and mirrors are used to control the amplitude division and recombination of the light beams, the output will fluctuate due to random noise perturbing the alignment of the optical components. To a very large extent, both the internal and external alignment problems are eliminated if the interferometer is constructed entirely from optical fibres allowing the possibility of a novel high resolution primary sensing element capable of remote operation.

Although the optical fibre approach solves the stability problem associated with all interferometers and has encouraged the development of guided wave systems for sensor applications, it does so at the cost of introducing a potentially major source of error, namely the variability of the optical constants of the fibre itself.

There are several other fundamental properties of all interferometers, whether implemented in a fibre optic or conventional form, which tend to restrict their use in sensor applications and are discussed further below.

2.2. Periodicity and dynamic range

From figure 1(b) we see that the output of the Michelson interferometer - as for all interferometers - varies with a periodicity of 2π rad, equivalent in this case to a change in relative mirror separation of $\lambda/2$. If it is used as a sensor and we require that its output is a unique function of mirror displacement, then the sensor must be operated in a 'zero pathlength difference' mode with an operational range of only $\lambda/4$, corresponding to 2×10^{-7} m for a typical solid-state laser source, with a wavelength of 8×10^{-7} m. Although it is possible in principle to construct an interferometer without any imbalance in its optical path it would require special techniques; consequently most interferometers are operated with an arbitrary optical imbalance between their arms, and displacement measurements are made relative to an initial unspecified OPD. Another consideration is that if reproducible relative optical displacement measurements are to be made then the optical pathlength of the reference (arm) must not change. Assuming that this can be achieved and the instrument is operated at the shot-noise limit, which typically corresponds to a displacement sensitivity of about 10^{-5} - 10^{-6} of an optical radian, then an optical sensor with a dynamic range (ratio of measurement range to resolution) of greater than 10^5 could be realised with a maximum displacement of only 2×10^{-7} m. If a specific application requires that the sensor operates over a much larger displacement range then it is necessary to retain both the current fringe number N (where a 'fringe' corresponds to an optical phase change of 2π rad, such that the total excursion of the Michelson interferometer is approximately $\frac{1}{2}N\lambda$) and also ascertain the 'direction' of the fringe motion to determine whether the optical path difference is increasing or decreasing. Various signal processing concepts (§6) have been developed which enable this information to be retained unambiguously *from an arbitrary starting point*; however, this information is usually lost when the system is switched off. If the application for the interferometric sensor is to obtain the amplitude of a periodic measurand, such as in surface vibration studies, then this problem does not arise. However, if the sensor is to be used for relatively slowly varying measurands, such as temperature, then this loss of information is unacceptable and the system will require initialisation every time it is switched on, see §8.3.3.

2.3. Linearised output

Again referring to figure 1(b) we see that the displacement sensitivity of the interferometer $(dI_D/d\phi) \propto \sin\phi$ varies periodically, being at a maximum when $\phi = \pm n\pi \pm \pi/2$ and zero when $\phi = \pm n\pi$ $(n = 0,1,2,\ldots)$. The point of maximum sensitivity corresponds to an OPD of $(2n + 1)\lambda/4$; this is the so called 'quadrature position'. In sensor applications it is important that the interferometer is effectively operated at constant linear sensitivity. Various signal processing systems to achieve this requirement are discussed in §6.

3. OPTICAL FIBRE WAVEGUIDES AND COMPONENTS

The complete analysis of waveguide propagation in optical fibres has been extensively treated by several authors (see, for example, Gloge 1971, Midwinter 1979) and only those fundamental aspects of the waveguide relevant to the practical realisation of optical fibre interferometers will be considered here.

At the most basic level, the waveguide can be considered to be an infinitely long two-component coaxial transparent medium. The central core which guides the light has a larger refractive index (n_1) than that of the outer cladding (n_2). In the ray-optics limit corresponding to fibre core diameters greater than 100 μm, the light will propagate without loss through the optical fibre provided it is launched into the central core such that it meets the core-cladding interface at an angle greater than the critical angle, $\theta_1 = \sin^{-1}(n_2/n_1)$. The guiding nature of the fibre is primarily determined by: (i) the core radius, a; (ii) its numerical aperture (NA), equal to $n_1(2\Delta)^{\frac{1}{2}}$ where $\Delta = [1 - (n_2/n_1]$; and (iii) the propagation constants of the light in the fibre.

Gloge (1971) has shown that Maxwell's equations, which describe the propagation of the light in the fibre, may be solved in the limit $\Delta \rightarrow 0$, corresponding to 'weak' guiding of the light. Gloge's analysis shows that in general there is not a unique 'optical path' for the injected light to follow as it propagates through the optical fibre, but a large number of paths, termed 'modes', which have different propagation constants. The propagation constant β of any guided mode in the fibre is defined by $\beta_2 < \beta < \beta_1$, where $\beta_2 = 2\pi n_2/\lambda$ and $\beta_1 = 2\pi n_1/\lambda$. The number of modes in the fibre, N, has been shown (Midwinter 1979) to be equal to $4V^2/\pi$, where V is the normalised frequency of the fibre equal to $(2\pi a/\lambda)(n_1^2 - n_2^2)^{\frac{1}{2}}$. When $V < 2.405$ then only the lowest order spatial mode, the LP_{01} mode, can propagate; and the fibre is classified as monomode. The LP_{01} mode comprises two independent orthogonal linearly polarised modes with propagation constants β_f and β_s equal to $2\pi n_f/\lambda$ and $2\pi n_s/\lambda$ respectively, where n_f and n_s are the refractive indices of the modes. Thus a monomode fibre element is birefringent and can be thought of as a general optical phase plate. The increases in the optical phase of two orthogonal linearly polarised light beams propagating in the eigenmodes of a birefringent fibre of physical length L are $\beta_f L$ and $\beta_s L$. The length L_p of the fibre over which these two orthogonal modes change their relative phase by 2π

rad is known as the 'beat length' of the fibre.

A typical optical fibre designed to be monomode at 633 nm will have a NA of about 6° and a core radius of 2.5 μm with a cladding radius typically between 40 to 60 μm; the whole fibre is usually coated in a soft polymer jacket (primary coating) to both protect ahd outer surface of the fibre and to give it mechanical strength.

If the V number of the fibre is greater than 2.405 then the fibre is multimode; in figure 2 the far-field patterns produced when a laser beam is propagated through separate multimode and monomode fibres are shown. The complex nature of the far-field pattern of the multimode fibre, figure 2(a), is readily distinguished from that of the simple gaussian profile of the monomode fibre, figure 2(b). Clearly it is not possible to fabricate a high contrast interferometer from multimode fibres as the

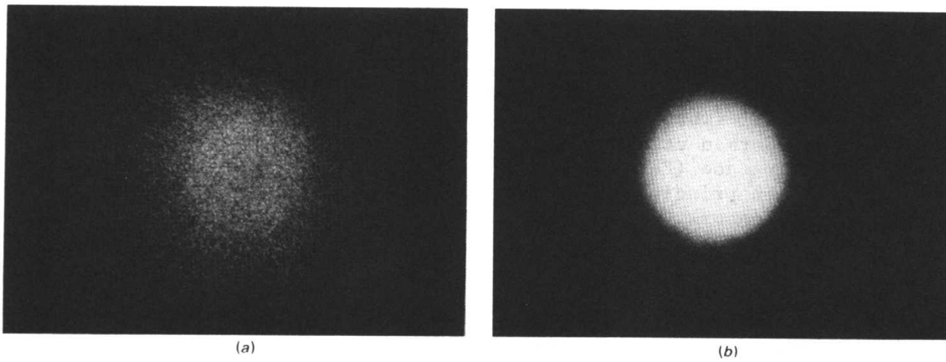

FIGURE 2. Far-field patterns observed when a laser beam is propagated through (a) a multimode fibre, (b) a monomode fibre.

multiplicity of guided 'light paths' will produce a similar multiplicity of interferometers and, as there will be arbitrary pathlength differences in each of these interferometers, the overall contrast will generally be both very poor and unstable. Even when the interferometer is made from monomode fibre, its transfer function will tend to be more complex than that of the conventional interferometer because of the birefringent nature of the medium guiding the light beams.

3.1. Specialised monomode fibres

As was stated above, monomode fibre supports the propagation of two orthogonally polarised modes; if the fibre core has perfect rotational symmetry then $n_s = n_f$, the modes are degenerate and the fibre shows no birefringence (Rashleigh 1983a); hence the polarisation state of the light remains constant as it propagates. As most commercial monomode optical fibres (primarily supplied for communications applications) are produced by pulling the fibre from a preform with a high degree of rotational symmetry in its refractive index profile, they usually exhibit relatively low birefringence, and are therefore also suitable for incorporation into fibre optic interferometers. Unfortunately, random levels of birefringence can be induced into the optical fibre by local twists or strains which are difficult to avoid when it is deployed as an interferometer. In addition to induced linear birefringence it is also possible that bends and twists in the fibre will cause random coupling between the orthogonal modes of the monomode fibre (circular birefringence); both these effects can combine to deleteriously affect the fringe visibility in the interferometer.

To overcome these problems, considerable research effort has recently been devoted to the design and development of special fibres for interferometric sensor applications. One approach has been to produce optical fibres with very high levels of 'built-in' birefringence as this tends to inhibit both externally induced mode coupling and bend birefringence. Highly birefringent fibre has been produced by several methods (Payne et al 1982); the fibre with the best polarisation holding parameter 'h' has been fabricated with internal stress lobes (Birch et al 1982). Highly birefringent fibres are often incorrectly called 'polarisation state maintaining fibres' although in general the polarisation state of the injected light is not maintained, in fact it is only preserved under special conditions - when the azimuth of an incident linearly polarised light beam is coincident with one of the eigenaxes of the fibre.

Monomode optical fibres with very low linear birefringence have also been developed (Norman et al 1979) to exploit magnetically induced circular birefringence (Faraday effect) (Smith 1978) for current measurement. Although in principle this particular fibre would be useful for interferometric sensors, its high susceptibility to externally induced birefringence has generally restricted its use in these applications.

3.2. Monomode fibre optic components

In order to implement all-fibre optic equivalents of the classical interferometers, it has been necessary to develop monomode fibre optic components to replace the conventional optical components such as beam splitters, mirrors, polarisers, etc. used in these instruments. Optical phase and frequency modulators compatible with the fibre optic waveguides are also required in order to recover the measurand-induced optical phase shift from the interferometer.

3.3. Directional couplers

Beam splitters - often called 'directional couplers' when implemented in optical fibre - have been developed at several laboratories and are discussed by D.N. Payne in this volume.

3.4. Mirrors

High quality, but low reflectivity mirrors can be readily implemented at the end of a monomode fibre by accurately cleaving the fibre at the desired position. Here the reflection coefficient of the mirror is determined by the Fresnel reflection coefficient and will be approximately 4%. Higher reflectivities can be obtained either by vacuum deposition of a dielectric or metal coating or, as has proved very successful in our laboratory, using a silvering solution commonly used to coat vacuum flasks. Several authors have attempted to attach conventional mirrors to monomode fibres; however, considerable difficulties are experienced with long term stability in the relative alignment between the mirror and the fibre end (Petuchowski et al 1981).

3.5 Joints

Permanent low loss joints can be made using a fusion process based upon a high voltage arc (Kato et al 1982). In the laboratory, however, recently introduced inexpensive commercial monomode connectors have been used very successfully in demanding applications such as the fibre optic gyroscope (Burns et al 1984).

3.6. Polarisers (wavelength selective attenuators)

Optical fibre polarisers have been made by selectively increasing the attenuation of one of the independent polarisation mode's propagation in the monomode fibre. This has been achieved by: (i) selective etching of the cladding to allow a metal coating to be deposited sufficiently close to the guiding core that it distorts the electric field of one of the propagating modes thereby greatly increasing the loss (Eickhoff 1980); and (ii) coiling the fibre at specific radius so that the bending loss for one of the propagating modes is greatly increased. Extinction ratios of greater than 25 dB have been obtained (Varnham et al 1983b) by this approach.

3.7. Phase modulators

Fibre optic phase modulators were first introduced by Davies and Kingsley (1974) for use in multimode fibre optic sensors; here the fibre is tightly wound around a large piezoelectric (PZ) cylinder. Applying a voltage to the PZ cylinder produces a redistribution of the light amongst the guided modes enabling a signal related to the movement of the cylinder to be superimposed on the far-field pattern of the output light emanating from the fibre. A similar concept has been used to produce a phase modulator for monomode fibre (Jackson et al 1980b). The monomode fibre is similarly tightly wound around a PZ cylinder but now the voltage-induced dimensional change of the PZ is used to alter the optical pathlength of the fibre. This type of phase modulator has virtually no insertion loss as the light is always contained in the fibre, and if many turns are wrapped around the cylinder only moderate drive voltages are required to produce optical pathlength changes of greater than 100 μm.

3.8. Frequency shifter

Bragg cells are commonly used to change the absolute optical frequency of a light beam; however, these components are not compatible with monomode optical fibre as the light has to be reinserted into the fibre after passing through the Bragg cell. Recently there have been reports (Nosu et al 1983, Risk et al 1984) of fibre optic based frequency shifters using acousto-optic modal coupling in highly birefringent monomode fibres. At the present time the reported efficiencies are very low, about 5%, and further development to increase this efficiency is necessary before they can be used for signal processing applications in monomode fibre interferometers.

4. CLASSICAL INTERFEROMETERS AND THEIR FIBRE OPTIC EQUIVALENTS

4.1. Two-beam: Michelson and Mach-Zehnder

The conventional Mach-Zehnder interferometer is shown schematically in figure 1(c) and although this configuration is slightly more complex than that of the Michelson interferometer, as it requires an extra beam splitter and mirror, it does offer two significant advantages over the Michelson interferometer. (i) Optical feedback to the light source is at a minimum - this is very important when laser sources are used as any out of phase light fed back into the laser tends to induce random changes in its optical output frequency (Kanada and Nawata 1979). (ii) There are two antiphase outputs from the interferometer which are equal in magnitude only at the quadrature point and therefore can be used as differential inputs for a servo to maintain the interferometer at maximum sensitivity; this approach also has the advantage that it tends to reduce the effects of intensity noise in the laser's output (Dandridge et al 1980a).

The all-monomode-fibre equivalents of both the Michelson and Mach-Zehnder interferometers are shown in figures3(a) and (b) respectively. In the case of the Michelson the conventional beam splitter is replaced with a monomode fibre directional coupler and the mirrors are formed by chemically coating the normally cleaved ends of the fibre (see §3.4). In the all-fibre Mach-Zehnder the directional couplers replace both the conventional beam splitters and mirrors. Indeed, it is this component which makes these interferometers unique, as it virtually eliminates all the effects of random mechanical disturbances which normally induce misalignment of the optical components in a conventional interferometer. Piezoelectric fibre phase modulators are readily incorporated into each configuration and can be used either to induce test signals or to form part of a 'quadrature' maintaining servo, as indicated in figure 3(c).

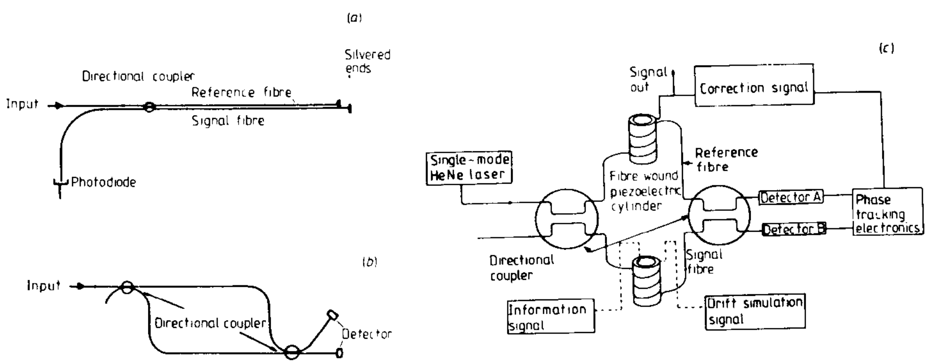

FIGURE 3. Fibre optic equivalents of the classical interferometers: (a) Michelson, (b) Mach-Zehnder, (c) fibre optic Mach-Zehnder test system incorporating piezoelectric phase modulators.

4.2. Multiple beam: Fabry-Perot

The classical Fabry-Perot interferometer (FPI) has the simplest configuration of all the interferometers as it is essentially an optical cavity formed by two ideal mirrors adjusted to be perfectly parallel with each other; again a requirement which is difficult to satisfy. The FPI can be used either in a reflection or transmission mode and its transfer function is described by the well known Airy function.

Fibre optic equivalents of the FPI are shown schematically in figures 4(a) and (b); in figure 4(a) the instrument is used in the conventional transmission mode and mirrors have been attached to the fibre ends to enhance the finesse (Petuchowski 1981). The alternative configuration, figure 4(b) is essentially a single section of monomode fibre with normally cleaved uncoated ends. The finesse will be low and the contrast of this FPI in transmission will be very poor; however, in back reflection, the transfer function and contrast are very similar to those of the

Michelson interferometer. The inherent simplicity of this fibre FPI, combined with the lack of ancillary optical components, tend to make the back reflection mode the most appropriate for sensing applications (Kersey et al 1983b).

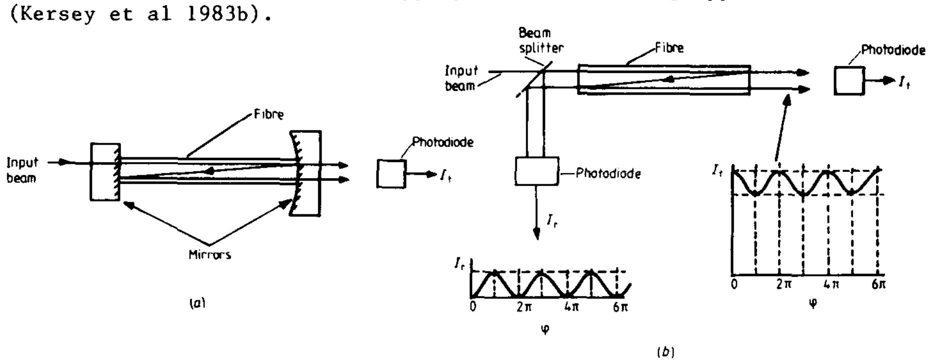

FIGURE 4. Fibre Fabry-Perot configurations: (a) mirrors attached to the fibre to enhance the reflectivity of the optical cavity, (b) FPI cavity formed by accurately cleaving the fibre ends; as indicated the FPI can be used either in reflection on transmission. The inserts show the transfer functions for reflection I_r, again ϕ, and transmission I_t against ϕ.

4.3. <u>Differential interferometer (polarimetric interferometer)</u>

Induced optical birefringence has been exploited for many years in the analysis of both static and dynamically induced strains in optical structures; for example, glass vacuum systems are usually examined between crossed polaroids to determine if the component has been properly annealed.

Differential interferometers are based upon the same fundamental principle and have been implemented using both monomode (Rashleigh 1980) and multimode (Jones and Spooncer 1983) optical fibres; both induced linear and circular birefringence have been exploited for sensor applications.

4.3.1. <u>Induced linear birefringence interferometer</u>. As was stated in §3, monomode optical fibres have two orthogonal polarisation modes which are degenerate in the limit that the fibre has rotational symmetry; however, if this rotational symmetry is broken, either by design in manufacture or through some extraneous perturbation such that the constituent atoms (or molecules) are subject to an anisotropic stress, the modes are no longer degenerate and have different propagation constants. The basic polarimetric sensor is shown in figure 5.

The polarised input beam is injected into the fibre such that it equally excites both eigenmodes of the fibre and can therefore be either linearly polarised with its azimuth at ±45° to the horizontal,

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} \quad \text{or} \quad \frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$$

or left or right circularly polarised,