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Sensors and Actuators A 113 (2004) 20–38

SENSORS AND ACTUATORS A PHYSICAL

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Review

Prospects for Fibre Bragg Gratings and Fabry-Perot Interferometers in fibre-optic vibration sensing

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Received 8 April 2003; received in revised form 9 December 2003; accepted 9 January 2004

Available online 10 May 2004

Abstract

Vibration monitoring of machinery is reducing the overall operating costs of industrial plants. Conventional vibration sensors, based on capacitive or piezoelectric principles, are limited in application due to the problem of electrical isolation. Fibre-optic based instrumentation is thus an attractive alternative method of vibration measurement in the vicinity of electrical substation. This paper discusses several techniques of vibration sensing using optical fibre technology and assesses their potential for use on electromechanical equipment. Firstly an overview of sensor based on In-Fibre Bragg Gratings is presented, and its potential for the measurement of strain and vibration is assessed. Secondly, vibration sensing using fibre-optic intensity-based measurement is presented and then Fabry-Perot Interferometer (FPI) for vibration sensing is critically reviewed. Of these, the FPI is the most attractive since it can easily be configured within a reflective fibre-optic probe. However, reported FPI sensors have been highly sensitive to measurement errors caused by mechanical vibration, temperature, and acoustic waves. This paper reviews technological developments of FPI to vibration sensing in extreme electromechanical environments and also for non-contact measurement. Finally this paper presents an overview of dual-wavelength technique for assessment of vibration signature.

Keywords: Vibration measurement; Fibre-optic sensor; Microdisplacement sensor; Fibre Bragg Gratings; Fabry-Perot Interferometer; EFPI; Dual-wavelength interferometer; Review

1. Introduction

Vibrations developed in industrial machines are vital indicators of their health. If a monitoring system records the vibration history, changing levels of vibration over time would warn a plant engineer of the need for maintenance to prevent breakdown or serious damage [1,2]. Expediting repairs by the early detection of faults would lead to considerable cost–benefits since it prevents major equipment damage, minimizes interruption to the production or supply system, and increases safety. Hence, a measurement system (instrumentation) for vibration analysis is of fundamental importance to industries operating heavy electromechanical equipment. Sensing elements for such instruments comprise displacement and velocity transducers, and accelerometers. Accelerometers are, perhaps, the most widespread, and are conventionally based on capacitive or piezoelectric principles. A piezoelectric accelerometer is an electromechanical device that produces an electrical output proportional to an applied vibratory acceleration. Piezoelectric transducers, however, are limited in application due to the problem of electrical isolation. They are thus not attractive for use in applications at high electric potential. Conductors connecting conventional sensors are susceptible to electromagnetic fields. Variations in line-voltage and ground loop problems can cause havoc with electrical measuring equipment. Lightning is another source of electrical noise that adversely effects these conventional measurements. Selection and installation of the sensor are important factors in diagnosing equipment vibration. Motion sensors provide data on displacement, velocity and acceleration, and their correct selection depends on the signal magnitudes and frequencies of interest.

1.1. Why a fibre-optic approach?

Conventional vibration sensors, based on capacitive or piezoelectric principles, are limited in application due to the

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doi:10.1016/j.sna.2004.01.043

problem of electrical isolation. Such sensors also suffer from malfunctions due to the presence of the high-voltages (typically 40 kV or more), high magnetic fields up to 5 T and the presence of the aggressive atmospheres (e.g. H_2 or SF_6 gas) of electrical circuit-breakers [3]. Fibre-optic based instrumentation is thus an attractive alternative method of vibration measurement in the vicinity of electrical substation [4–6].

1.2. Solution using fibre-optic instrumentation

Optical fibre sensors were just introduced in the late 1970s. These technologies, combined with advances in optical transducers, have enabled remote vibration monitoring using compact portable instrument packages. With inherent electrical isolation, superior dielectric properties and immunity to electromagnetic interference, fibre-optic sensors (FOS) offer remote vibration measurements in highly localized parts of electrical machinery.

The advanced laser-based measurement techniques have a number of significant advantages over other sensors for monitoring of vibration. In particular, it offers a non-contact perturbation-free means of monitoring test-objects. Such laser and fibre-optic technologies are providing a new approach to vibration monitoring in electromechanical equipment.

Interferometric techniques are particularly attractive as they offer the highest measurement sensitivity. Mach-Zehnder, Michelson, Sagnac, and Fabry-Perot (FP) interferometers have all been reported in the literature [7–31] for use in fibre-optic sensing configurations. Of these, the FP interferometer is the most attractive for this work since it can easily be configured within a reflective fibre-optic probe. However, reported FP sensors have been highly sensitive to measurement errors caused by mechanical vibration, temperature, and acoustic waves [18–31]. Hence, the motivation in the review work is to identify a more practical FP sensor for monitoring vibration.

There are many fibre-optic vibration sensors described in the literature [29–45], those based on interferometric encoding via optical phase modulation offer the highest sensitivity. In previous paper, we introduced a critical review on speckle-pattern based vibration sensing in electromechanical equipment [46] for measuring microdisplacement and vibration. In the present contribution this paper reviews several techniques of vibration sensing using optical fibre technology (based on Fibre Bragg Gratings (FBGs), intensity-based and FPIs) and assesses their potential for use on electromechanical equipment. Finally this paper presents a review of dual-wavelength signal-interrogation techniques for the assessment of vibration signature.

2. Vibration sensor based on In-Fibre Bragg Gratings

The Fibre Bragg Grating is one of the most exciting developments in the field of fibre-optic sensing in recent years. Photosensitivity in optical fibbers is the main phenomenon involved in writing Bragg gratings into the core of a fibre [47,48]. The most important advantage of an FBG sensor is that the measurand is encoded directly in terms of wavelength, which is an absolute parameter [49]. Hence, the output signal is independent of the intensity of the source, and losses in the connecting fibers and couplers. Furthermore, an array of wavelength-multiplexed FBGs may easily be implemented for simultaneous multiple measurements.

In this section, an overview of FBG sensor technology is presented, and its potential for the measurement of strain and vibration is assessed.

2.1. Principles of FBG-based sensing

Fibre Bragg gratings are periodic structures that are imprinted directly into the core of glass optical fibers by powerful ultraviolet (UV) radiation. Such structures consist of a periodically varying refractive index (RI) over typically several millimeters of the fibre core. The specific characteristic of FBGs for sensing applications is that their periodicity causes them to act as wavelength sensitive reflectors.

During the imprinting process, the intensity of the UV illumination is made to occur in a periodic fashion along the fibre core. At a sufficiently high power level, local defects are created within the core, which then give rise to a periodic change in the local refractive index. The changes of index created in this way are relatively permanent and are sensitive to a number of physical parameters—notable examples being pressure, temperature and vibration. Thus, by monitoring the resultant changes in reflected wavelength, FBGs can be used in a variety of sensing applications to measure physical quantities such as strain, temperature, pressure, ultrasound, high magnetic field, force and vibration. One of the most important applications of FBG sensors is as part of a ‘fibre-optic smart structure’, in which an embedded FBG array is used for quasi-distributed measurement of strain within a composite body.

Fig. 1 shows, diagrammatically, the variation of the refractive index along the length of an FBG with δn being the depth of RI modulation.

In a single-mode optical fibre, light is guided along the axis of the core in the fundamental mode. When the light passes through an FBG, Fresnel reflections take place due

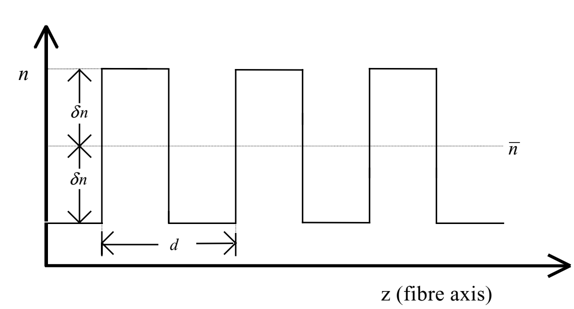

Fig. 1. Refractive index profile of an FBG.

to the variations in refractive index. This is called coherent reflection. If the wavelength of the incident light satisfies the Bragg condition for constructive interference [47], then

$$\lambda_B = 2\bar{n}d \quad (1)$$

where λ_B is the Bragg wavelength, $\bar{n}$ the average refractive index of the FBG, and d is the grating period. If $\delta\lambda$ is the range of the wavelength on which the grating is highly reflective then $\delta\lambda/\lambda_B = \delta n/\bar{n}$. When the Bragg condition is satisfied, reflections from each successive period will be in phase. Light that does not satisfy the Bragg condition passes through the FBG as if it were of uniform refractive index $\bar{n}$ [47].

2.2. History of FBG development

FBG development extends from approximately 1978, when light from an argon-ion laser was first launched into a fibre using a microscope objective and an interference pattern was generated along the fibre core by forward and backward propagating signals [48,50]. In 1989, it was demonstrated that exposure of a length of fibre core to an interference pattern of UV light at 245 nm could produce a periodic variation of refractive index that acted as a diffraction grating [51]. Many methods have been found to increase δn by improving both the UV exposure method, and the photosensitivity of the fibre core [52]. Transverse holographic methods are particularly useful for producing the modulated UV since they can easily create FBGs with both the desired spectral response and at any position along the fibre [53]. The strength of the FBG reflectance peak during the imprinting process increases with exposure to the UV radiation.

In 1993, an advanced FBG production technique was reported [54,55], which involved the use of an optical phase mask to generate interference fringes. Similar techniques for FBG production are used in most current FBG sensor work. Recently, it has been demonstrated that FBG sensors have great potential for a wide range of applications where quasi-distributed measurements of physical parameters such as strain, pressure, vibration, temperature, ultrasound, high magnetic field and high-g acceleration are required [56–66].

2.3. The FBG sensor

The potential of FBGs for use as sensors was recognized shortly after the discovery of FBGs. Particular effort was directed towards developing detection circuitry suitable for demodulating the reflected FBG spectrum into an electrical signal. A typical FBG sensor system is illustrated in Fig. 2, in which a fibre y-coupler directs light from a light source to the FBG and then splits off the modulated signal to a detector.

The primary advantage of FBG sensors is their capability for multiplexed operation. A large array of FBG sensors may be addressed by a single source and detector using one or more of three standard techniques: time division multiplexing (TDM), frequency division multiplexing (FDM) and wavelength division multiplexing (WDM).

2.3.1. FBG sensor using time division multiplexing

A schematic diagram for the TDM approach is shown in Fig. 3 [57]. The sensors have to connect in such a manner that there will be a time delay between the returning signals from the individual gratings. A pulsed laser source is used for this purpose. The pulse, which must be shorter than the round trip time between reflections, is launched along a chain of identical FBGs. The reflected FBG signals are directed to a photodetector via a coupler. Individual FBG signals are then separated in times using switching electronics. The TDM approach is able to multiplex a large number of FBG sensors without the need for wavelength selective components.

2.3.2. FBG sensor using frequency division multiplexing

A schematic diagram for the FDM approach is shown in Fig. 4 [57]. A wavelength controlled laser source is used to address a chain of identical FBGs. The source has a periodically modulated chirp in frequency that is smaller than the line width of the gratings. The reference signal from the first coupler interferes with the reflected FBG signals. If the FBG sensors operate at different frequencies, the signals from each can be separated using switching electronics.

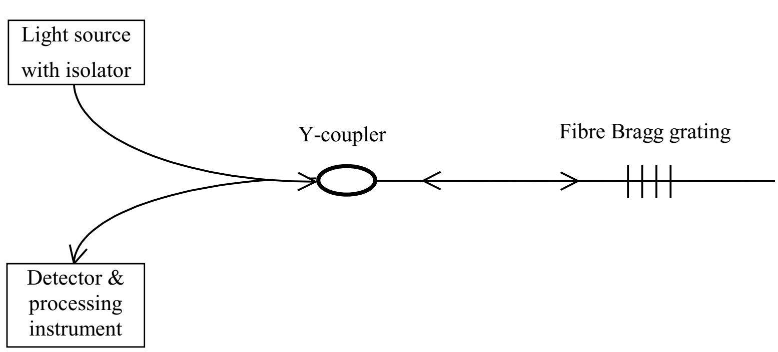

Fig. 2. Schematic of a typical FBG sensor system.

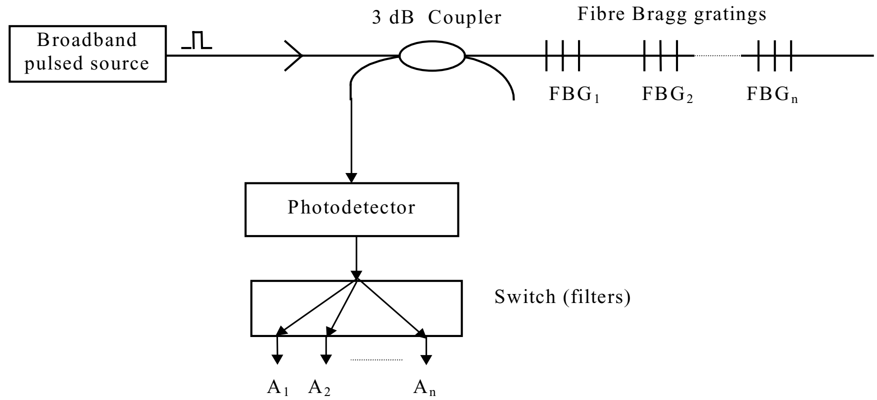

Fig. 3. Schematic diagram for a TDM FBG sensor system [57].

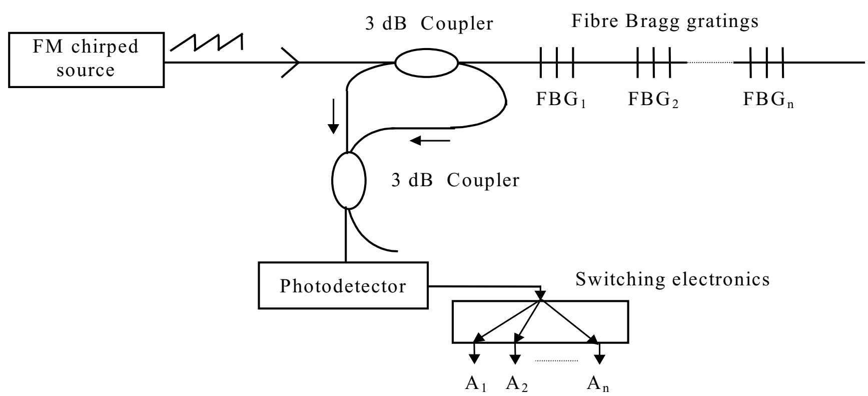

Fig. 4. Schematic diagram for an FDM FBG sensor system [57].

Successful demultiplexing relies on no overlap between the FBG modulation frequencies.

2.3.3. FBG sensor using wavelength division multiplexing

A schematic diagram for the WDM approach is shown in Fig. 5. A broadband source is used to interrogate a chain of wavelength-multiplexed FBGs.

Since FBGs have a wavelength selective reflection, they lend themselves conveniently to wavelength multiplexing schemes. A quasi-distributed chain of FBGs would then be multiplexed in the wavelength domain to separate the individual sensor signals. The FBG sensors would be assigned an operating wavelength band wide enough to cover the measurand-induced wavelength shift without overlap [57].

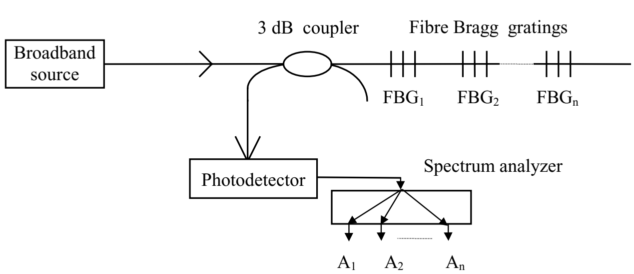

Fig. 5. Schematic diagram for a WDM FBG sensor system.

2.3.4. FBG interferometric sensors

For many applications where one wants to measure quantities such as electric and magnetic fields, acoustic waves, or very small temperature or strain changes, the wavelength shift of the FBG may not be sufficient to give a good measurement. The sensitivity can be enhanced by using pairs of FBGs as the reflectors of a Fabry-Perot Interferometer (FPI). In this case, the measurand acts on the fibre between the FBGs and small phase shifts can be detected. By coating the fibre between the gratings with an electric, magnetic, or acoustic enhancing coating, the technique can be used to measure particularly small changes in these measurands [57].

2.4. Applications of FBG sensors

2.4.1. Strain measurements

When an FBG is strained, the Bragg wavelength changes due to both the changed grating spacing and a photoelasticity-induced change of the refractive index. The photoelastic component is determined by the photoelastic constant, which for silica is 0.22. The Bragg wavelength thus changes with applied stress [57]. Fig. 6 illustrates a typical technique for wavelength encoding the output from a narrowband FBG strain sensor. Here, the FBG sensor is

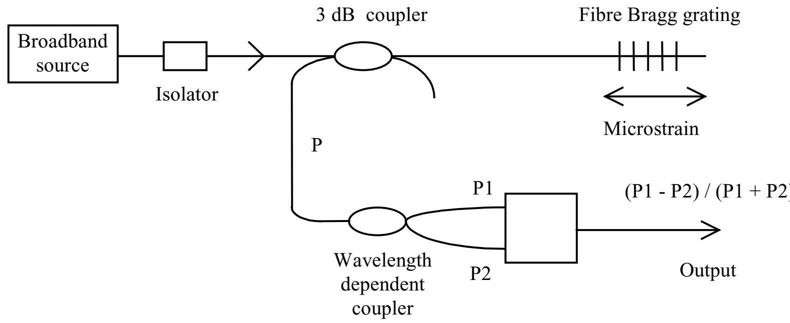

Fig. 6. Strain measurement using an FBG sensor and a wavelength-dependent division coupler [61].

connected to a broadband source via one port of a 3 dB coupler. The FBG signal returned through this coupler is directed towards a wavelength dependent coupler while being blocked from the source by a fibre isolator. Detection of the output intensity from both ports (P1 and P2) of the coupler and the use of simple electronic processing reveals a voltage directly proportional to the FBG strain [61].

2.4.2. Vibration measurements

2.4.2.1. Vibration due to strain. Using a single FBG sensor in conjunction with an unbalanced fibre interferometer wavelength discriminator, vibration can be detected with high resolution [59]. Wavelength-shift of the FBG detected in this way results in an interferometric signal output $I(\lambda)$ which may be expressed as

$$I(\lambda) = A\{1 + b\cos(\varphi(\lambda) + \phi)\} \quad (2)$$

and

$$\varphi(\lambda) = \frac{2\pi n\delta L}{\lambda} \quad (3)$$

where λ is FBG wavelength, A a constant depending on the light source and coupling losses, b the fringe visibility, ϕ the phase difference between the interferometer arms, φ the induced phase shift, n the refractive index of the interferometer medium and δL is the optical path-difference (OPD) between the interferometer arms.

If the wavelength-shift of the FBG is $\delta\lambda$ and the fibre strain is $\delta\sigma$, then $\delta\lambda = k\ \delta\sigma$, where k is a constant depending on the strain-to-wavelength-shift responsivity of the FBG. Thus, the change of phase shift can be expressed from Eq. (3), as [59]

$$\varphi(\lambda) = -\frac{2\pi n\delta L}{\lambda^2}\delta\lambda \sin\omega t \quad (4)$$

where $\delta\lambda \sin\omega t$ is the dynamic strain-induced modulation of the reflected wavelength. A schematic diagram of the reported system is shown in Fig. 7.

The FBG sensor is attached to a piezoelectric transducer that produces a dynamic strain. The reflected wavelength-modulated light is processed by means of an

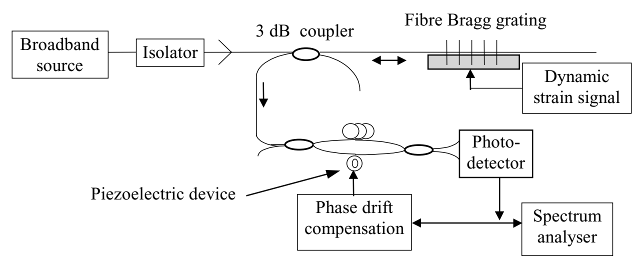

Fig. 7. Vibration measurement using an FBG sensor [59].

imbalanced Mach-Zehnder interferometer. One arm of the interferometer is phase-modulated via a fibre-stretching piezoelectric device with detector feedback for phase drift compensation. Experimental results show that the FBG wavelength shift is proportional to the applied strain, and that the dynamic strain sensitivity is nearly $0.6n\varepsilon/\sqrt{\text{Hz}}$ at frequencies above 100 Hz.

2.4.2.2. Acceleration due to strain. Theriault et al. [65] demonstrated a technique to measure acceleration using an FBG (Fig. 8). The technique is based on fibre elongation with strain, which increases the period of the grating and shifts the spectral response toward longer wavelength. The sensing element involves an FBG in a short length of single-mode optical fibre that is clamped in a mount with 1 cm of free fibre to stretch or compress. The spectral profile of the reflected signal depends on the strain distribution produced along the length of the FBG. The system operated linearly with applied acceleration up to $170{,}000g_n$, where g_n is the free fall acceleration (9.8 m/s^2).

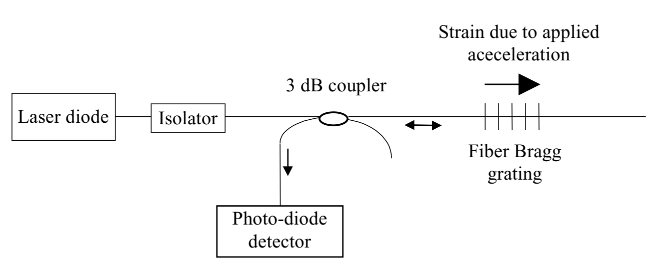

Fig. 8. Acceleration measurement using an FBG sensor [65].

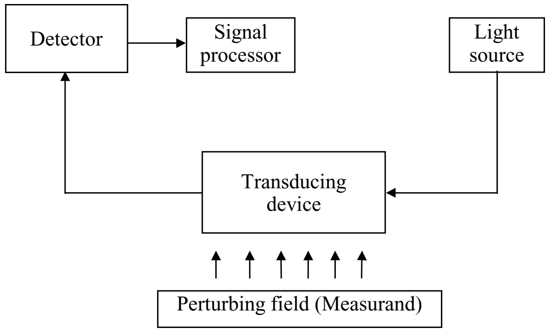

Fig. 9. Basic configuration for intensity-modulating systems.

2.5. Discussion on vibration sensor based on In-Fibre Bragg Gratings

A brief description is given of FBGs and their sensor applications. FBGs have many advantages for use as sensors. FBG sensors provide an absolute measurement insensitive to adventitious fluctuations in intensity, since their output signal is wavelength-encoded. FBGs can easily be tailored for different reflectivities and bandwidths, and the fibre preparation during the writing process is minimal, requiring only the temporary removal of a small section of the coating. FBG sensors are inherently small and, comprising little more than an optical fibre, are considerably less complex than other proposed types of fibre sensor. FBG sensors are particularly suited to surface-mounting or embedding, and are very strong candidates for the generation of smart structures [62,66]. The FBG has also proven to be a powerful tool for some sensing applications within the electric power industry, e.g. the measurement of transformer-winding temperature [64], high-*g* acceleration [65].

The FBG sensor is also a capable device for the monitoring of dynamic strain [59]. However, FBG vibration sensors are not suitable for a non-contact method of measurement.

3. Vibration sensing using intensity-based measurement

Many fibre-optic sensors based on intensity modulation techniques have been demonstrated in past years (during 1980–1990). Some of these techniques; fibre microbending, fibre-to-fibre coupling, moving masks/gratings and modified cladding, are described by Giallorenzi et al. [67], Culshaw [68] and Pitt et al. [69,70]. A wide range of measurand fields can be measured using various configurations of these incoherent sensors [71,72]. A general schematic for systems based on intensity-modulated signals is shown in Fig. 9. With signal transmission based generally on multimode fibers, such systems are very simple in concept, reliable, low cost and offer a relatively high measurement sensitivity, primarily via the initial conversion of the measurand to displacement. However, in many cases, a referencing mechanism is necessary to maintain a

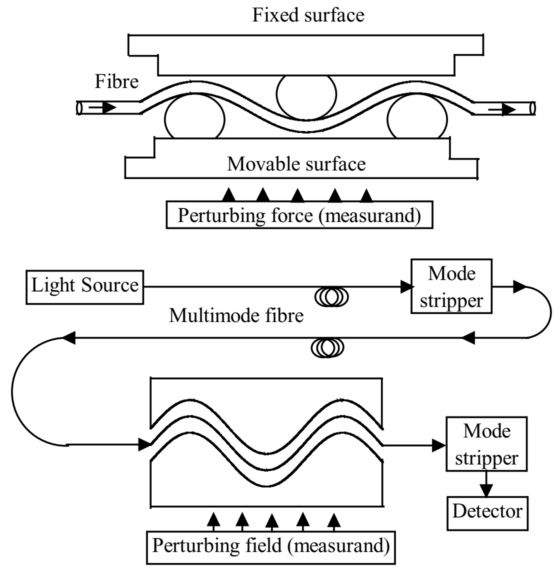

Fig. 10. Intensity-based system incorporating fibre microbending losses.

calibrated output of the sensor and thus obtain an accurate measurement [73,74]. Without referencing, an additional error will be introduced due to optical power fluctuations in the light source, couplers, connectors or any other optical components in the system. An intensity-based FOS in a reflective configuration is an appropriate incoherent means of measuring microdisplacement [75,76].

3.1. Reported sensing configurations

A fibre microbending type of intensity-based FOS was reported by Pitt et al. [70]. The system, shown in Fig. 10, utilizes a force sensor in which a fibre is placed between two corrugated plates. On application of a vibrating body to one corrugated plate, the induced fibre microbending leads to an optical transmission loss that is a measure of the applied force or vibration. Indirectly, the system can also be used for the measurement of small displacements. Step-index MMF is particularly suitable for this type of microbending loss sensor.

Kersey et al. [73] described an intensity-based closed-loop system for displacement measurement, as shown in Fig. 11.

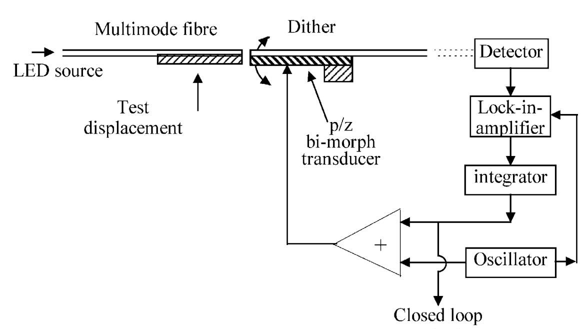

Fig. 11. Intensity-based closed-loop system for displacement measurement.

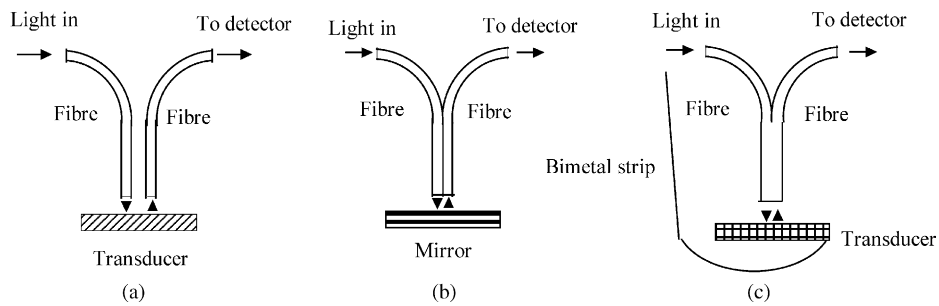

Fig. 12. (a–c) Reflective configurations of intensity-based displacement sensor.

In this system, two coaxially aligned multimode fibers are butted in a fibre-to-fibre coupling technique. The position of maximum coupling can be determined by applying a small displacement dither ($y_0 \sin \omega_0 t$) to one fibre, and monitoring the harmonic content of the variation in the coupled intensity received by the other. As the system is symmetrical, the maximum coupling state can be characterized by a null in the amplitude of the intensity modulation developed by the dither frequency ω_0. The null response is maintained via feedback to a bi-morph transducer attached to the receiving fibre. Displacement of the input fibre, which is allowed to move under perturbation by the measurand field, is then determined via the location of the receiving fibre.

In another example, an intensity-based displacement sensor can be realized by guiding light through the fibre onto a reflective material whose reflectance changes in accordance with the measurand. Lewis et al. [75] and Murray et al. [76] demonstrated configurations in which the collection of the reflected light is either by a second fibre or the same incident fibre (Fig. 12). The transducer itself may be a simple mirror surface that is attached either to the surface of a vibrating body or a bimetallic strip.

Lourenco et al. [74] described the intensity-based displacement-sensing configuration shown in Fig. 13. In this configuration, the movement of a piston changes the displacement between the fibre end-face and a reflective surface within the sensor head. The intensity of the signals at detectors 1 and 2 can be expressed as

$$I_1 = I_0(1 - C)C\alpha^2 M \quad (5)$$

$$I_2 = I_0 C\alpha \quad (6)$$

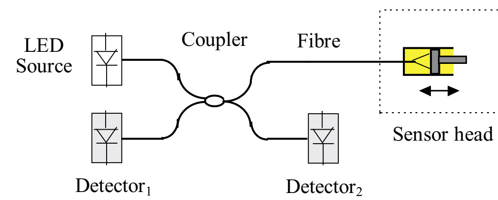

Fig. 13. Reflective intensity-based displacement sensor with source–intensity referencing.

where I_0 is the intensity of light source, C the splitting ratio of the coupler, α the coupler losses and M is the modulation factor introduced by the sensing technique. The ratio I_1/I_2,

$$\frac{I_1}{I_2} = (1 - C)\alpha M \quad (7)$$

is thus independent of the power of the light source, and linearly proportional to the modulation factor. This intensity-referenced system thus first performs the division of two analogue detector outputs and then estimates the displacement of the moving piston via a PC program. However, the arrangement suffers the added complexity of comparison, arithmetic operations, convolution and PC-based digital signal processing.

Recently, Gangopadhyay et al. [29,31] described an alternative intensity-based sensor configuration for vibration measurement. The sensor, shown in Fig. 14, is both extrinsic and reflective. The design uses two multimode (50 μm/125 μm) fibers for signal transmission, and a movable reflective surface for signal transduction. The presented design thus acts as a simple proximity transducer in which displacement of the reflective surface is encoded as a varia-

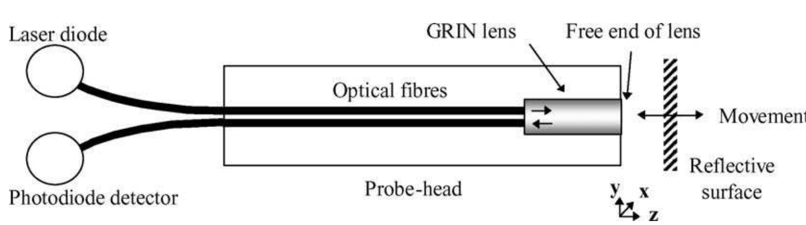

Fig. 14. Intensity-based multimode sensor design.

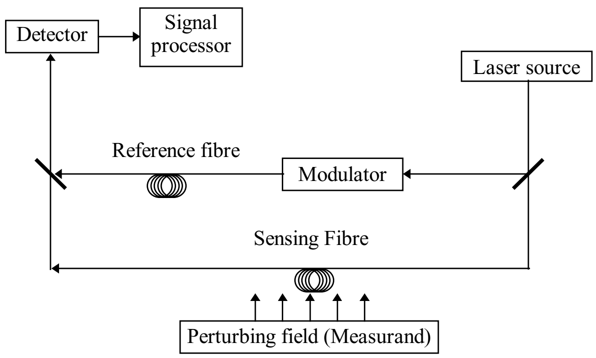

Fig. 15. Basic configuration for phase-modulated sensors.

tion in signal intensity caused by changing geometric path between the two fibers. This sensor has a demonstrated displacement measurement range of 4.5 mm with a resolution of better than 25 μm and its potential applications include displacement measurement in mechanized, high-voltage and hazardous environments.

3.2. Discussion on intensity-based vibration sensing

The capabilities of intensity-based fibre-optic sensors are discussed. Although easy to build, a disadvantage common to all unreferenced intensity-based FOS systems is measurement error due to adventitious changes in signal intensity. Referencing for source–intensity fluctuations is relatively easy to implement. However, the measurement accuracy will still be degraded over long periods due to signal-level changes caused, for instance, by losses in the sensor head and changes in detector sensitivity. The need for complex referencing arrangements to overcome adventitious changes of intensity, makes intensity-based systems relatively unattractive.

While the discussed intensity-based sensing techniques are principally concerned with the measurement of displacement, it is thus believed that an interferometric approach is more suited to the transient monitoring needs for fibre-optic vibration sensor. Such an approach (Fig. 15), based on phase-modulated signal processing, would eliminate the need for complex intensity referencing, and provide increased measurement sensitivity and accuracy.

4. Vibration sensing based on Fabry-Perot Interferometer

While the beam-splitting requirements of Mach-Zehnder, Michelson and Sagnac interferometers present significant impediments to both miniaturization and embedding, the classical Fabry-Perot Interferometer has a convenient 2-mirror cavity arrangement which can be used in either reflection or transmission, and needs neither a reference arm nor sophisticated stabilization [7]. Of the various reported FPI-sensing schemes suited to displacement or vibration, most utilize a quadrature-based measurement for increased sensitivity. Quadrature-based systems which need active phase-control [24] or sophisticated signal-recovery techniques [25] tend to be expensive and complex. However, one scheme utilizes a relatively simple quadrature setting via a wavelength-tuned laser-diode source [77], while another avoids quadrature entirely via a more complex arrangement of two sensing heads [78]. Such schemes are establishing FPI as a versatile tool for fast and sensitive vibration analysis, which can automatically monitor extended surfaces in real-time without contact or perturbation, and which can be combined with fibre-optic signal transmission for rugged performance in harsh engineering environments.

This section reviews FPI based vibration sensing and assesses its potential for use on electromechanical equipment.

4.1. Principles of FPI based sensing

The FP cavity is the most convenient interferometric configuration as it is simply formed from the space between two, typically parallel, mirror surfaces. The round-trip phase-lag ϕ within such a cavity is given by [79].

$$\phi = \frac{2\pi(2nd\cos\theta)}{\lambda} \tag{8}$$

where n is the refractive index of the medium between the mirrors, d the mirror separation, θ the angle of incidence and λ is the propagating wavelength. If the cavity is air-filled ($n = 1$, and λ can be approximated by its free-space value λ_0) and the incident illumination is normal ($\theta = 0$), Eq. (8) becomes

$$\phi = \frac{4\pi d}{\lambda_0} \tag{9}$$

4.1.1. High finesse operation

The use of a pair of mirrors of high reflectivity, R, creates a one-dimensional resonating optical cavity known as an FP-etalon. Acting essentially as a periodic ultra-narrow linewidth filter, the FP-etalon outputs a series of sharp peaks (or fringes) in wavelength space when the small fractions of escaping light due to multiply reflected beams are additive in phase. For an FP-etalon viewed in reflection, the intensity I_R of these fringes is given by [80].

$$I_R = \frac{F\sin^2(\phi/2)}{1 + F\sin^2(\phi/2)} \tag{10}$$

where

$$F = \frac{\pi}{2\sin^{-1}((1-R)/2\sqrt{R})} \tag{11}$$

is the finesse of the cavity. Exploiting changes in I_R due to changes in cavity length is attractive for signal transduction

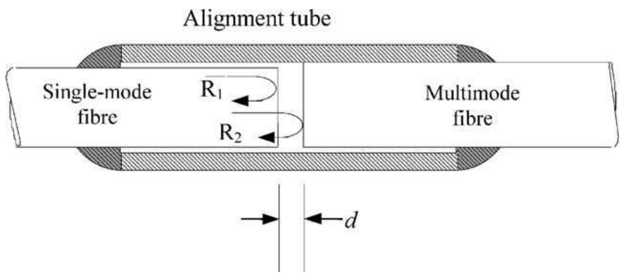

Fig. 16. Geometry of a reflective FPI sensor defined by two fibre end-faces [24].

as multiple passes within a high finesse cavity increase the sensitivity with respect to other types of interferometer.

4.1.2. Low-finesse operation

Low-finesse cavities, in which one or both mirror reflectivities are low, however, are more commonly used in sensing applications. The operation of such cavities may be dominated by a single reflection. Fig. 16 is an example of a reflective sensing configuration with a bulk-optic FP cavity and fibre-optic signal transmission described by Murphy et al. [24]. The input side of the cavity is via a single-mode fibre. The other side of the cavity is the end-face of a multimode fibre. R_1 and R_2 are the reflectivities of the cavity surfaces, and d is the cavity length. An air-filled FP cavity ensures low-finesse operation. R_1 and R_2 are then determined simply by the reflectivity of an air–glass interface—in this case $\approx$0.02.

By applying the plane-wave approximation to the interference of superimposed signals from a two-wave interferometer [7,24,81,82], the reflected intensity I_R from the FPI can be expressed as

$$I_R = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_1 - \phi_2) \quad (12)$$

where A_1 and A_2 are the amplitude coefficients of the reflected signals due to R_1 and R_2, and ϕ_1 and ϕ_2 are their corresponding phase-lags. The subscripts 1 and 2 refer, respectively, to the reference and sensing signals of the FPI. Rewriting for convenience $A_1 = A$, and using $R_1 = R_2 = R$, the amplitude coefficient of the sensing signal, A_2, can be expressed as [24,83]

$$A_2 = A\left(\frac{Tr}{r + 2d\tan[\sin^{-1}(\mathrm{NA})]}\right) \quad (13)$$

where $T = 1 - R$, r is the radius of the fibre-core, d the distance separating the mirror-surfaces, and *NA* is the numerical aperture of the fibre defined by

$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2} \quad (14)$$

with n_1 and n_2 representing, respectively, the refractive indices of the core and cladding of the fibre. Assuming no further optical loss and using $\phi_1 - \phi_2 = \phi$, the intensity detected from the low-finesse FP cavity, I_{det}, can now be written as [24]

$$I_{det} = A^2\left[1 + \left(\frac{2Tr}{r + 2d\tan[\sin^{-1}(\mathrm{NA})]}\right)\cos\left(\frac{4\pi d}{\lambda_0}\right) + \left(\frac{Tr}{r + 2d\tan[\sin^{-1}(\mathrm{NA})]}\right)^2\right] \quad (15)$$

4.2. Measurement performance

An attractive feature of interferometry for measurement purposes is its sensitivity and absolute calibration. Optical phase-modulation encodes signals on the wavelength-scale of light. By mixing phase-modulated light with a reference signal, the FPI produces an optical output consisting of a series of light and dark fringes, which are of high contrast if the relative phase is constant across the region of mixing. In a typical reflective FPI sensor, the static input mirror of the cavity provides the reference signal, while the other mirror provides the phase-modulated signal by being attached to the vibrating surface being monitored. As one fringe is equivalent to a change in optical path-difference of one wavelength, the equivalent displacement recorded by a reflective FPI sensor in air ($n = 1$) is a half-wavelength. The displacement D of the vibrating surface is thus given by

$$D = \tfrac{1}{2}N\lambda_0 \quad (16)$$

where N is the number of fringes. Due to the periodicity, fringe-counting methods [21,84,85] may be used to determine displacements over multiple wavelengths.

The power signal-to-noise ratio of a PIN-diode optical heterodyne-detector is generally given by [86].

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{(2\eta\varepsilon^2/h\nu)P_1P_2}{2\,\Delta f(P_1 + P_2) + (h\nu kT_a\,\Delta f/e^2\eta R_L)} \quad (17)$$

where η is the quantum efficiency of the detector, $0 < |\varepsilon| < 1$ the heterodyning efficiency, h the Planck's constant, ν the frequency of the light, Δf the bandwidth of the detector, P_1 and P_2 are the powers of the two beams incident on the detector, k the Boltzmann's constant, T_a the absolute temperature of the detector, e the charge of the electron, and R_L is the load resistance. We have assumed that dark current and background light may be neglected. In an FPI system, P_1 relates to the reference beam and P_2 relates to the beam reflected from the target. For systems with a high fringe contrast, $P_1 \approx P_2 = P$, giving

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{(2\eta\varepsilon^2/h\nu)P^2}{4\,\Delta fP + (h\nu kT_a\,\Delta f/e^2\eta R_L)} \quad (18)$$

4.3. Forms of fibre-optic FPI sensor

A number of FPI sensing configurations of great sensitivity have been reported, including those with conventional cavities, solid etalons and fibre-optic resonators. FPI vibration sensors may either be extrinsic so that the FP cavity is external to the transmitting fibre, or intrinsic so that FP

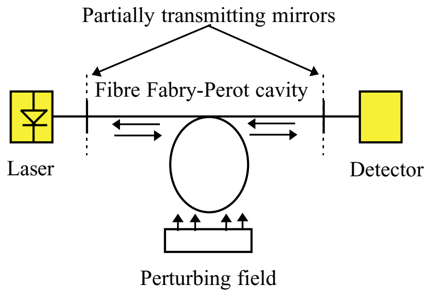

Fig. 17. Schematic diagram of a simple FFPI sensor system.

cavity is contained within the transmitting fibre. FP sensing cavities may also be used either in transmission or reflection.

4.3.1. In-Fibre FP Interferometry

Fig. 17 shows a simple vibration-sensing configuration in which a partially transmitting mirror surface is applied to either end of a length of optical fibre to produce the FP cavity. When the partial mirror-surfaces are inside the fibre, the configuration is known as an in-fibre Fabry-Perot Interferometer (FFPI).

In 1982, Yoshino et al. [81] demonstrated detection of impact vibration using a 10 m singlemode FFPI with 70% end-reflectance. A schematic diagram of the developed system is shown in Fig. 18. An output in the form of changed optical fringes was obtained when a mechanical impact was applied to the optical bench. The impact strength was sufficient to induce phase modulation of several π in the fibre.

In 1983, Kersey et al. [20] demonstrated a single-mode FFPI with uncoated fibre ends as an accelerometer. The experimental set up is shown in Fig. 19. With 10 turns of fibre wound on a solid rubber cylinder and a loading mass of 0.2 kg, the system had a phase sensitivity of $\geq$200 rad/g up to the resonant frequency of 150 Hz. The minimum detactable phase shift was 10^{-5} rad at 1 kHz, and 4×10^{-5} rad at 100 Hz, giving a limiting sensitivity of 2×10^{-7} g with a peak of 3×10^{-8} g at the 150 Hz resonance.

Kist et al. [21] studied a FFPI strain gauge sensor element manufactured from gradient index fibre. The approach featured easy coupling between the input and output fibers as well as a modular concept of constructing both transmissive and reflective forms of FFPI sensor, as shown in Fig. 20. A fringe-counting method was used to determine the excursion of a cantilever at increments of 0.2 μm.

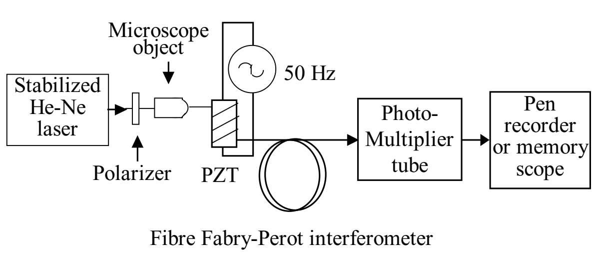

Fig. 18. Schematic diagram of an FFPI sensor system used to detect impact vibration [81].

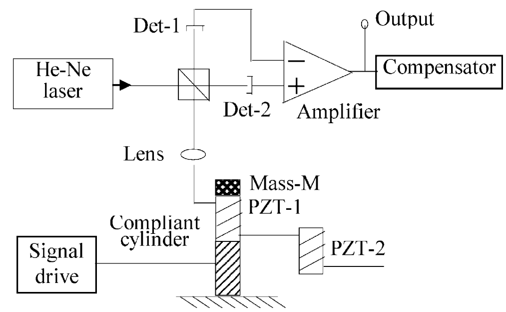

Fig. 19. Schematic diagram of an FFPI sensor system used as an accelerometer [20].

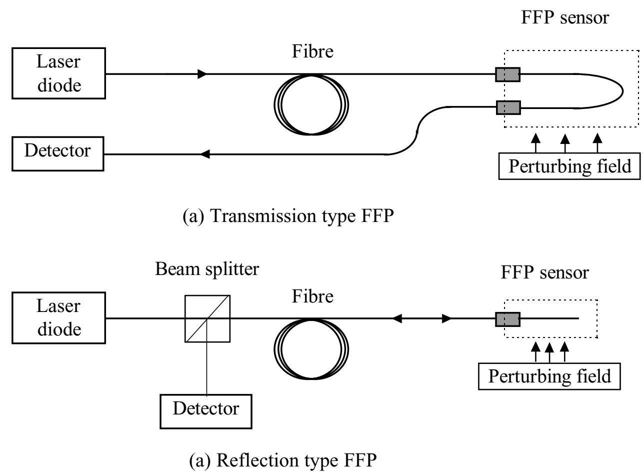

Fig. 20. A modular approach to the construction of transmission- and reflection-type FFPI sensor systems [21].

4.3.2. Extrinsic FP interferometry

Sensors based on extrinsic Fabry-Perot interferometry (EFPI) have been discussed by a variety of authors. In 1993, Sudarshanam and Claus [78] demonstrated an EFPI system with quadrature phase biasing (Fig. 21). The configuration

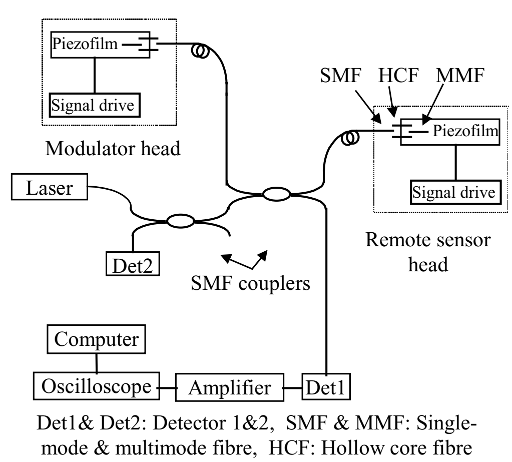

Fig. 21. Split-cavity cross-coupled EFPI sensor system [78].

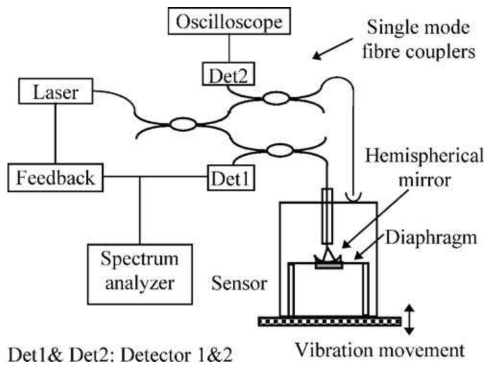

Fig. 22. Hemispherical air-spaced EFPI sensor system used as an accelerometer [87].

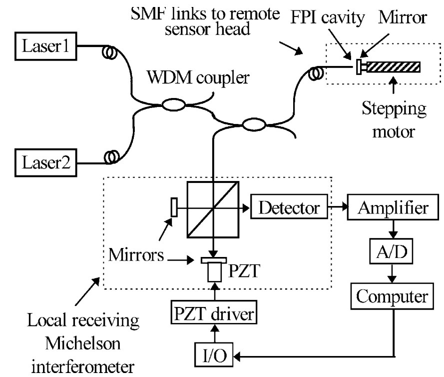

Fig. 24. EFPI sensor system using a synthesised (white-light) source [90].

utilized two sensor heads on a single directional coupler in a split-cavity cross-coupled EFPI to provide four-beam interference. The need for quadrature phase biasing is eliminated using a spectrum analysis detection scheme.

In 1989, Gerges et al. [87] demonstrated a technique to measure acceleration using a hemispherical air-spaced EFPI and a weighted diaphragm (Fig. 22). The technique involves attaching a hemispherical mirror to the diaphragm and then using EFPI to measure its displacement. The sensing element is a loaded elastic diaphragm with a rigid disk at the center. The measured optical phase changes versus frequency were combined with the 4×10^{-5} rad/$\sqrt{}$Hz phase resolution to calculate the acceleration resolution. The cross sensitivity to orthogonal components of acceleration was measured to be better than −32.1 dB.

In 1992, Chen et al. [88] demonstrated an EFPI constructed by using multimode optical fibers (50 μm/125 μm step-index). They demonstrated that if certain precautions are followed in the sensor head and system design, multimode optical fibers are capable of transmitting a stable phase signal with a good SNR in an optical fibre interferometric configuration. An FPI system is used as sensing interferometer and a processing interferometer is used to convert the phase information into an intensity-modulated signal (Fig. 23). To verify the common-mode condition theory, the angle between the two mirrors of the FPI cavity was increased by tilting second-mirror. The signal visibility was monitored as a function of the increase in tilting-angle.

In 1993, Belleville and Duplain [89] demonstrated a white-light EFPI strain gauge constructed by using multimode optical fibers (50 μm/125 μm step-index). The FPI cavity length was measured with the help of a fizeau interferometer. They demonstrated that the sensor is perfectly linear, with a sensitivity estimated at $0.25\mu\varepsilon$ and a range of strain adjustable to $10{,}000\mu\varepsilon$.

In 1995, Rao and Jackson [90] described a long-distance fibre-optic white-light displacement sensing scheme using an EFPI at the remote sensing end, with the sensor signal being interrogated by a local receiving Michelson interferometer (Fig. 24). A source synthesized from the combined outputs of two low coherence sources at wavelengths of ∼1.3 and ∼1.57 μm made precise identification of the peak of the central fringe possible. The FP cavity was formed between the cleaved end of the fibre and a mirror attached to a dc stepping motor. Using a cavity length of 500 μm, the system achieved a displacement-range to resolution of better than 10^4:1. The system is thus suitable for any measurand such as strain or vibration that can be transduced to displacement.

In 1996, Bhatia et al. [28] demonstrated an absolute EFPI system for measuring values of cavity length d ranging from 40 to 300 μm (Fig. 25). With a demonstrated spectral

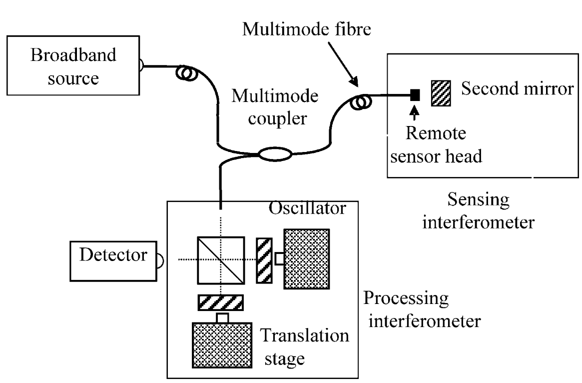

Fig. 23. Absolute EFPI sensor system constructed by using multimode fibers [88].

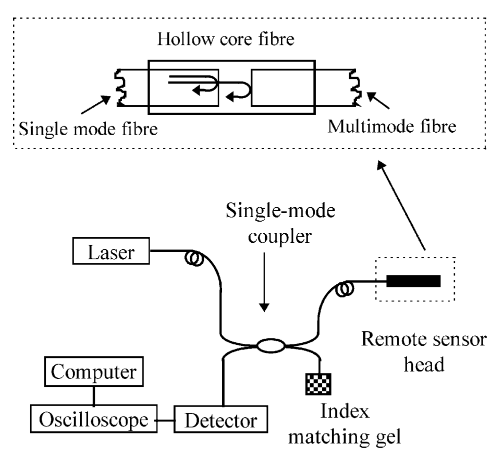

Fig. 25. Absolute EFPI sensor system [28].

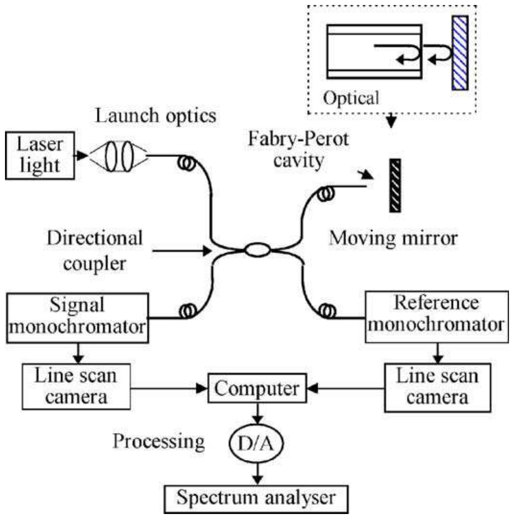

Fig. 26. Miniature EFPI sensor system with passive signal processing [26].

resolution of 0.1 nm, the system was successfully applied to measuring the strain induced in a concrete specimen with internal axially loaded reinforcement rods. A thin layer of metal, such as gold or aluminium, was deposited on the ends of the two fibers enclosing the cavity to increase the interface reflectivity and hence enhance the finesse of the cavity.

In 1996, Ezbiri and Tatam [26] demonstrated a passive signal-processing technique for a miniature low-finesse EFPI based on a phase-stepping technique (Fig. 26). An FP cavity length of 174 μm was demonstrated as both a vibration and temperature sensor. The technique featured auto-compensation for errors due to higher order reflections, 50 dB dynamic range and 9 mrad $Hz^{-1/2}$ sensitivity at 40 Hz.

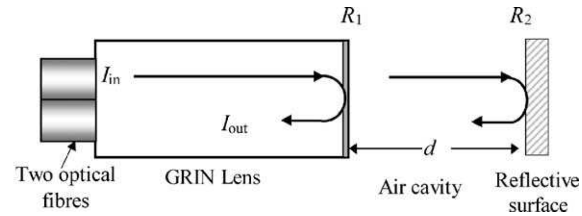

Fig. 28. Geometry of a reflective FPI sensor with two multimode fibre [29].

In 1998, Mio et al. [91] studied an EFPI system with birefringent mirrors for detecting extremely small vibration. The technique exploited the polarization change of the transmitted cavity light caused by the natural birefringence appearing on interferential mirrors—an effect, which is enhanced by the cavity resonance. Since there were no additional polarization-changing elements within the cavity, a high finesse was achieved which was indispensable for sensitive vibration measurement.

In 1997, Gangopadhyay et al. [29] demonstrated a system employing an alternative EFPI configuration for the sensing of vibration and is shown in Fig. 27. The sensor probe, shown in Fig. 28, utilizes a simple extrinsic FP cavity in a reflective configuration [29–31]. An adjacent pair of 50 μm/125 μm step-index multimode optical fibers couple light into and out of the cavity. Illumination is provided by a low-power laser diode. A movable reflective surface acts as the transducing device and a 0.25-pitch gradient-index rod (GRIN) lens is used for efficient light-guiding between the input and output fibers. A coating of partial reflectivity R_1 on the output face of the GRIN lens provides the interference reference. A reflective surface of reflectivity R_2 moves in sympathy with the target vibrations, providing the interference signal. The FP cavity has a length d in air. With this scheme, static calibration demonstrated a displacement

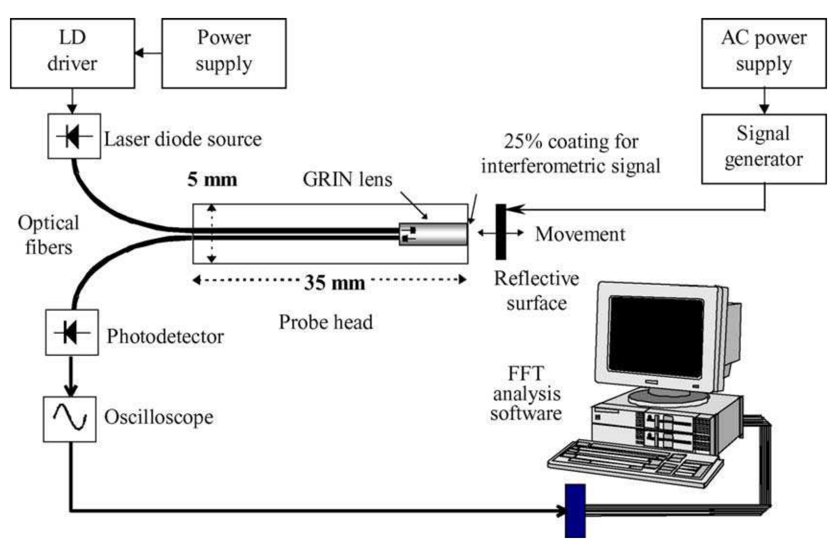

Fig. 27. Proposed multimode EFPI sensor system [29,31].

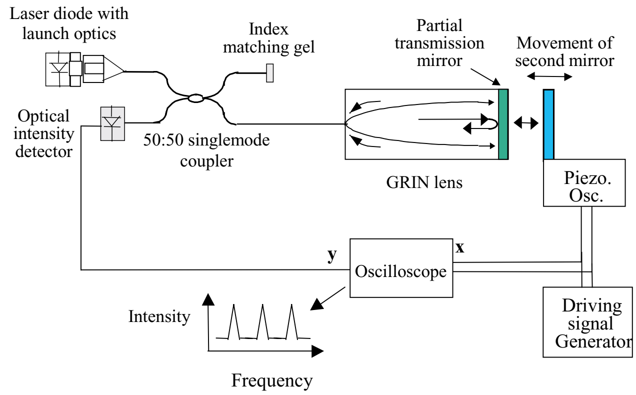

Fig. 29. Proposed singlemode EFPI sensor system [31,92].

measurement range of 20 μm giving a measurement resolution of better than 0.033 μm [29]. With the same scheme the displacement measurement further enhanced to 39 μm [30]. Dynamic tests demonstrated a working range of at least 3.74 μm at 2 kHz [31].

In 1999, Gangopadhyay et al. [31,92] demonstrated a simple variation of the EFPI vibration sensor using singlemode fibre. Shown in Fig. 29, the sensor system is supplied by one singlemode 4 μm/125 μm fiber pigtail and adjacent launch optics (instead of the multimode fibre pair). The pigtail is spliced to a 2×2 singlemode fiber-optic coupler. Back reflection from the fourth and unused fiber port is avoided by immersion in index-matching gel. Illumination is provided by a laser-diode (SHARP LT024MD) emitting at 780 nm. The sensor probe, shown in Fig. 30, utilizes a simple extrinsic FP cavity in a reflective configuration butted with one single-mode fibre [31,92]. The sensor uses the same coated GRIN lens and movable reflector (as in the multimode fibre probe). Demonstrated result shows a dynamic working range of at least 4.29 μm at 2 kHz [31] and the measurement is further enhanced to 13.26 μm [92].

4.4. Discussion based on vibration sensor using Fabry-Perot interferometry

Fabry-Perot interferometry is the most sensitive and exciting tool in the field of optical metrology. This section reviews its methods and application to vibration sensing. By combining optical fibers together with solid-source laser sources, FPI systems excel in their flexibility, sensitivity, and ability to provide real-time measurements of surface vibration. Systems based on FFPI and EFPI are easy to implement and are free from false signals due to reference-arm perturbation. EFPI with CW illumination is in common use for spectral analysis.

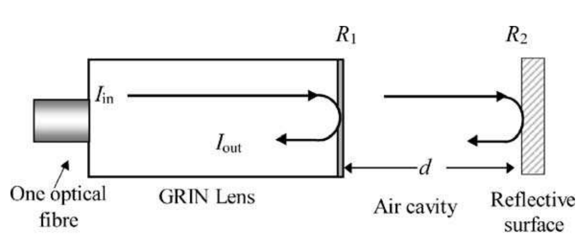

Fig. 30. Geometry of a reflective FPI sensor butted with one SMF [92].

EFPI combined with fibre-optic data-transmission appears most suited to harsh engineering environments such as high-voltage circuit-breakers and other electromechanical equipment. For these applications, the main challenges are the monitoring of simultaneous multiple frequencies and transient events.

FPI sensors with singlemode fibre transmission are relatively new but appear to be the most suited to high-frequency monitoring in industrial environments. In conclusion, this review is concerned with the performance, implementation and applications of measurement systems based upon fibre-optic versions of the classical Fabry-Perot Interferometer.

5. Dual-wavelength technique for assessment of vibration signature

Fibre-optic sensing instrumentation needs to transform the optical signal from the sensor into an electrical signal as a real representation of the physical parameter to be measured. For sensing purposes and to evaluate small vibration signal via an interferometric method, it is often sufficient and even useful to work with a low-finesse Fabry-Perot cavity so that the signal is of $\cos\phi$ shape, where the phase ϕ is related to the measuring parameter like vibration that changes in time [21]. The principle of operation of quadrature phase-shifted and dual-mode interferometric sensors has been described in detail by Keiser [83].

There are various methods to evaluate the optical signal from an interferometer. Amongst these, dual-wavelength signal processing is a strong candidate. In this technique, the optical path-difference between the two beams of an interferometer is determined within a certain range by interrogating the phase of the interferometric signal at two wavelengths [93]. The range over which the OPD can be uniquely determined is set by the separation of the source wavelengths. Dual-wavelength interferometric processing has been discussed in a number of contributions by Kersey and co-workers [94–96]. The technique can be utilized as a signal-processing scheme for the vibration sensor since this utilizes an extrinsic Fabry-Perot Interferometer (EFPI) with a transfer function very similar to that of a two-beam interferometer.

This section reviews dual-wavelength processing scheme for the measurement of vibration and assesses its potential to overcome direction ambiguity problem during vibration measurement.

5.1. Principle of operation for dual-wavelength EFPI

An EFPI vibration-sensing configuration with dual-wavelength illumination is shown in Fig. 31. As the

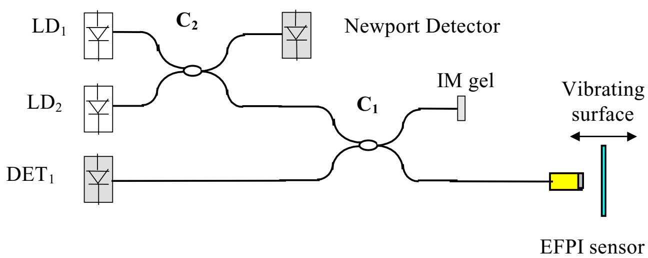

Fig. 31. EFPI vibration-sensing configuration with dual-wavelength illumination.

configuration is based on a two-wave interferometer, its output intensity I can be expressed as

$$I = I_0(1 + V\cos\phi) \tag{19}$$

where I_0 is the mean fringe intensity, V the fringe visibility, and ϕ is the phase delay between the sensing and reference signals. If the EFPI has a path-length l, ϕ can be expressed as

$$\phi = \frac{2\pi nl}{\lambda} \tag{20}$$

where n is the refractive index within the EFPI and λ is the propagating wavelength.

A classical technique for extending the measurement range and determining the order of interference is to illuminate the interferometer with two optical sources of wavelength λ_1 and λ_2, each of which alone would produce a unity visibility interferogram [97,98]. The interferometer signal can then be written as

$$I = I_0[1 + \cos\phi_1] + I_0[1 + \cos\phi_2] \tag{21}$$

where $\phi_1 = 2\pi nl/\lambda_1$, and $\phi_2 = 2\pi nl/\lambda_2$. For a practical EFPI, the cavity medium is air ($n = 1$) and $l = 2d$ where d is the distance between the two mirrors (Fig. 32). Now

$$I = I_0\left\{1 + V\cos\left[4\pi d\left(\frac{\lambda_1+\lambda_2}{\lambda_1\lambda_2}\right)\right]\right\} \tag{22}$$

where the visibility of interference V_{dual} is given by

$$V_{dual} = \cos\left[4\pi d\left(\frac{|\lambda_2-\lambda_1|}{\lambda_1\lambda_2}\right)\right] \tag{23}$$

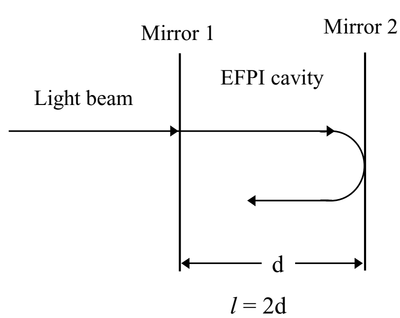

Fig. 32. Light propagation within an EFPI cavity.

If the two sources have a relatively small wavelength separation, they combine to generate an effective wavelength λ_e given by

$$\lambda_e = \left(\frac{\lambda_1\lambda_2}{|\lambda_2-\lambda_1|}\right) >> \lambda_1 \quad \text{or} \quad \lambda_2 \tag{24}$$

In this case, the unambiguous range of the interferometric output becomes λ_e so that the limitation of the relatively small unambiguous range of single−wavelength detection is overcome [13].

Practical implementations of the technique include illuminating the interferometer at λ_1 and λ_2 sequentially in time, and the use of wavelength selective detectors so as to measure the interferometer phases $\phi_1 = 2\pi nl/\lambda_1$ and $\phi_2 = 2\pi nl/\lambda_2$ explicitly. A high resolution output can be obtained from either of these phases. The measurement range can then be defined as

$$\phi_1 - \phi_2 = 2\pi nl\left(\frac{|\lambda_2-\lambda_1|}{\lambda_1}\right) \tag{25}$$

Dual-wavelength techniques determine the interference order as well as the phase difference, thus allowing the absolute value of a measurand to be determined over a much wider unambiguous range when the sensor is initialized. The difference in the phase shift varies linearly with both the optical path-length l and the wavelength difference ($|\lambda_2 - \lambda_1|$), and can exceed more than 100 individual interferometic fringes in practical systems [93].

One way of implementing dual-wavelength interrogation is by current modulation of semiconductor laser diodes. The effect of this is to induce an amplitude modulation due to change in the laser's operating point and a frequency shift due to the alteration of the optical path length of the laser cavity [99]. This frequency shift can be used to obtain FM modulation in coherent optical systems [100].

In 1986, Beheim [101] demonstrated a fibre-optic interferometer which uses dual frequency modulated laser diodes and a two-fibre configuration (Fig. 33). One singlemode input fibre launches light into the sensor and one multimode fibre (50 μm/125 μm step-index) transmits the modulated signal to a phase measurement circuit. Advantages of this

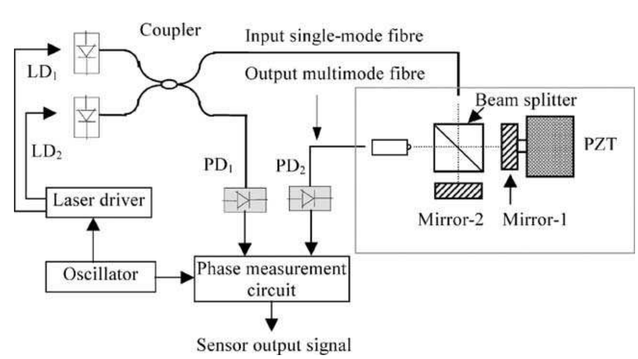

Fig. 33. Schematic diagram of a dual-wavelength interferometer with a multimode output fibre [101].

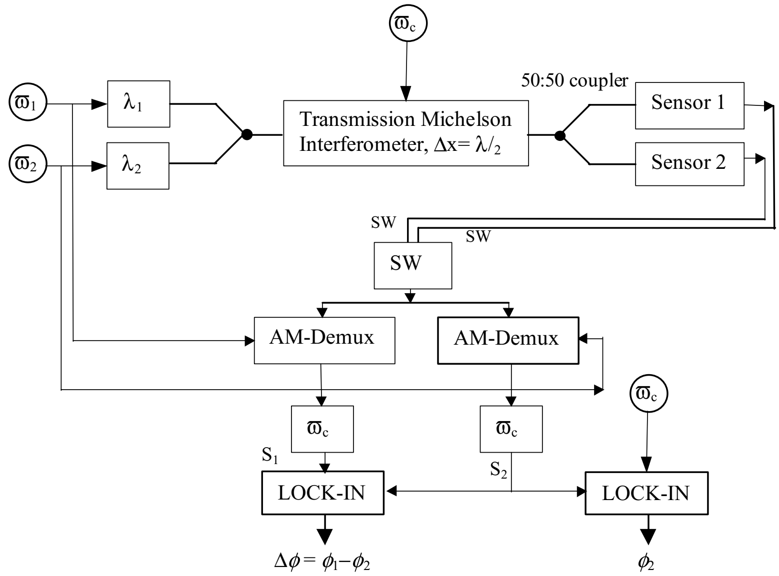

Fig. 34. Schematic arrangement of a multiplexing sensor network with dual-wavelength signal processing [93].

technique include high immunity to the effects of optical loss and compatibility with inexpensive multimode fibre-optic components.

An extension of such frequency modulation technique, Webb et al. [97] demonstrated a technique for extended-range interferometric measurement by combining coherence multiplexing with dual-wavelength processing. In this technique, the interferometer is illuminated with a single source and the two wavelengths are obtained at the output by means of an interference filter. The system is complex and the resolution of the interferometric measurement is 7.5°, limited primarily by thermally and mechanically induced movement of the mirrors (used in interferometer), and perhaps by drift within the phase detection circuitry. The coherence length of the unfiltered spectrum limits the range of relative phase measurement and hence it is not possible to extend the range of the system by the full 2π differential phase change.

In the similar attempt, Ribeiro et al. [93] demonstrated a multiplexed displacement sensor network which combines dual-wavelength signal processing (Fig. 34) with low coherence interferometry. The system uses two multiplexed bulk-optic Michelson interferometers and two multimode laser-diode sources (SharpLT023MC) with central wavelengths of 781 and 789 nm for dual-wavelength operation. The fringe visibility at the output of each sensor is ~30%. The system uses two switches. When switch-1 is 'on', sensor-1 outputs s_1 and s_2 (corresponding, respectively, to λ_1 and λ_2) are in quadrature, i.e. $\Delta\phi = 90°$. Similarly, when switch-2 is 'on', sensor-2 outputs s_1 and s_2 are in phase, i.e. $\Delta\phi = 0°$.

A system for detecting the vibration of a flexible beam by means of a two-wavelength fibre-optic Michelson interferometric sensor was reported by Chien et al. [13]. The system exploited synthetic wavelength and heterodyne signal processing to obtain a wide dynamic range and linear scale factor. The system is complex, the sensor is integral (and thus not suitable for point measurements), and additional phase-bias stabilization-loop may be required to avoid ambient disturbance.

In addition to the above reported results, a comprehensive review of literature had been carried out. Most of the systems in which many difficulties have been encountered, an ideal dual-wavelength sensor device can play a special role due to its practical viability. It appears that the dual-wavelength interrogation technique can be implemented with the help of the proposed EFPI in two different ways: (i) by current-induced frequency modulation of a single laser-diode source connected with the sensor system or (ii) by using two separate wavelengths from two laser diodes with the sensor system. In the first method, a frequency-modulated source can increase the effectiveness of the interferometer by exploiting the mutual frequency-shift between the output signals. The laser-diode frequency is controlled via its drive currents [99]. An advantage of the first method is that a single source is easier to stabilize for its intensity. For the second method, two different laser sources are required which should be independently intensity stabilized. The second method uses two fibre-couplers (one for coupling laser signal to the sensor head and another for returning the modulated signal to the detector) and time-delay circuitry to drive the two laser diodes. Also, a synchronous detector circuit may be required to capture the sensor outputs.

An EFPI vibration-sensing configuration with dual-wavelength illumination [102] is shown in Fig. 31. The system uses two AlGaInP laser diodes (Hitachi HL6726MG) pigtailed to monomode optical fibre. The central emission wavelengths of the diodes are 670 nm (LD_1) and 682 nm (LD_2). The wavelength difference between the laser diodes is 12 nm giving $\lambda_{eff} \approx 36\,\mu m$. The optical output from the two pigtails (of average total power $\approx 60\,\mu w$) is directed towards the vibrating surface via two single-mode 50:50 fibre couplers. C_2 is the coupler for the laser diodes and C_1 is the coupler for the sensor head. One output arm of C_2 is used as an intensity reference by means of a Newport detector. The other output arm of C_2 illuminates C_1. One output arm of C_1 illuminates an EFPI (optical gauge) having a sinusoidal transfer function. The other output arm of C_1 is immersed in index-matching (IM) gel to eliminate back reflection.

LD_1 and LD_2 are modulated by a square wave of (chopping) frequency ranging from 1 to 100 kHz via a programmable signal generator (Hewlett-Packard HP33120A), and a time-delay driving circuit is used. The signal from the EFPI is monitored at DET_1 using an IPL (10539HAL) photodiode in conjunction with a simple detector circuit. The interference signal using the output of either LD or the combined output of both LDs can be captured on one output channel using DET_1. When both LDs are in operation, synchronous detection may be used to separate and output the two interference signals on different channels.

5.2. *Discussion on dual-wavelength signal processing for assessment of vibration signature*

The main requirement to use dual-wavelength signal-interrogation technique is to resolve the direction ambiguity in interferometric multi-fringe responses generated by a single-wavelength interferometer. In this section, the principle of operation of an absolute fibre-optic signal-processing scheme has been discussed. The scheme employs dual-wavelength signal processing and has been demonstrated in conjunction with a miniature low-finesse EFPI sensor. Absolute fibre-optic sensors are expected to play a vital role in the growing need to monitor the vibration of electromechanical equipment.

The performance of the dual-wavelength signal-processing scheme depends on the absolute stabilities of the source wavelengths, which are known to be temperature dependent. Therefore, to ensure that there are no errors in the determination in the fringe number, fringe contrast and measurement range, both laser sources must be temperature stabilized.

6. Conclusions

Due to the problems of electrical isolation and electromagnetic interference, and the need for non-contact measurement, conventional piezoelectric instrumentation was shown not to be well suited to the application such as electromechanical equipment. A fibre-optic solution was thus sought. A survey of fibre-optic vibration instrumentation showed that intensity-modulated systems are attractive for their simplicity, while phase-modulated systems offer high measurement sensitivity.

Hence, this paper reviews several techniques of vibration sensing using optical fibre technology and assesses their potential for use on electromechanical equipment. In the review part, firstly an overview of sensor based on In-Fibre Bragg Gratings technology is presented, and its potential for the measurement of strain and vibration is assessed. Secondly, vibration sensing using intensity-based measurement is presented. Finally, the Fabry-Perot Interferometers (In-fibre Fabry-Perot and extrinsic Fabry-Perot) for vibration-sensing technology are critically reviewed. In this part, a non-contact vibration-monitoring technique based on transient measurements from an extrinsic Fabry-Perot Interferometer is also assessed. At the end of this paper the dual-wavelength signal-processing techniques are also briefly reviewed. Hence, the interferometric implementation was assessed in conjunction with an absolute processing scheme for the measurement of vibration. It was observed from the review that the phase-detection ambiguity of single-wavelength interferometers can be overcome using dual-wavelength interferometers.

In conclusion, the power industry, where the monitoring of small displacement with complete electrical isolation is essential (for instance, within generators, motors, mechanical turbines and precision universal ac/dc motors), fibre-optic sensors are most useful. Most of these areas need the reflective extrinsic type of monitoring. Some of the sensor configurations reported in this review article thus have potential applications in a much wider range of engineering environments.

Therefore, it is the author's belief that, in the future, when the fibre-optic instrumentation presented in this paper fulfils its potential as a means for vibration measurement, it would also find wider application in other engineering fields.

Acknowledgements

T.K. Gangopadhyay acknowledges the support of the Director, Central Glass and Ceramic Research Institute (CSIR), Calcutta, India and Australian Agency for International Development (presently AusAID). The author would like to acknowledge Associate Professor A.D. Stokes and Dr. G.E. Town of the School of Electrical and Information Engineering, Sydney, NSW 2006, Australia. T.K. Gangopadhyay is grateful to Dr. Philip J. Henderson, Kent University, UK, for his generous help, encouragement and suggestions in this research for several occasions.

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Biography

Tarun Kumar Gangopadhyay was born in Gopalpur, WB, India in 1959. He graduated bachelor of electrical engineering with first class in 1989 and master of electrical engineering in 1991 with first class, both from the Jadavpur University, Calcutta, India. He carried out research in the area of 'Fibre-optic transducers' in his thesis submitted for master degree. He joined in the Dishergarh Thermal Power Station, India, working in the area of 'power generation and transmission'. Later he was appointed as electrical engineer in the Central Glass and Ceramic Research Institute (CSIR), India. There he carried out research work in the area of 'development of varistor materials for high-voltage applications'. During 1995–1999, he went to Australia in AusAID scholarship for commonwealth countries and there he was involved in the research and development of optical fibre vibration sensors for electrical power industry with High Power Testing and Optical Fibre Sensors Group, School of Electrical and Information Engineering, The University of Sydney, Australia. He worked there in the field of intrinsic and extrinsic single-mode fibre-based sensors and fibre-optic interferometry. He has got many awards and prizes for his research work from The University of Sydney and Australian Photonics. He visited many countries for attending international conferences.

He has authored several journal papers and international conference papers. He has done some theoretical research work and publication jointly with the University of Kent, Canterbury, UK.

He is currently involved in R&D work of optical fibre fabrication and characterization, fibre-optic amplifier and fibre-optic components such as bi-directional coupler, WDM coupler in Central Glass and Ceramic Research Institute (CSIR), Kolkata, India. His current research interests are development of Fibre Bragg Grating sensors, bio-medical sensors and PM fibre coupler for Gyro application. He is a member of IEEE, OSA and The Institution of Engineers, India.