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(54) Optical fibre strain sensor

(57) An optical fibre strain sensor, e.g. for monitoring the condition of a solid propellant body for a rocket motor, includes a sense fibre (39) in contact with the body. A signal from a first modulated laser source (32) is coupled to the sense fibre via a downlead (36) and reflected at 40. A reference signal from a second, identically modulated, laser source (33) operating at a different wavelength traverses the downlead and is reflected at 38. Weighted summation of the two signals (figure 3, not shown) removes crosstalk introduced by wavelength multiplexing couplers (37, 41) whereby to allow accurate phase comparison to obtain a measure of strain in the sense fibre. The use of a separate reference source overcomes the problem of spurious signals arising from strain in the downlead providing coupling to the sense fibre.

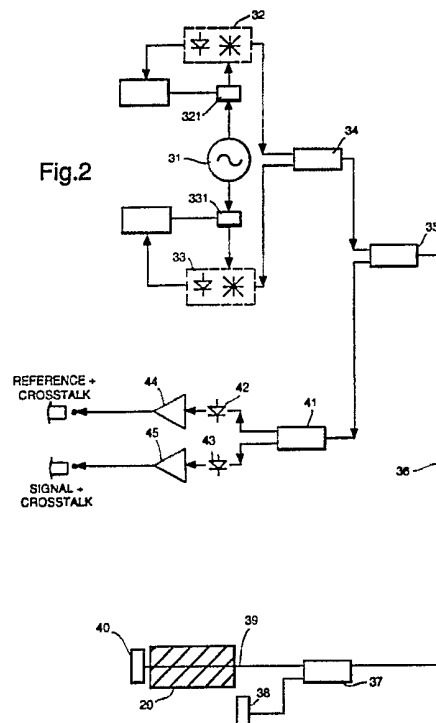


Fig.1

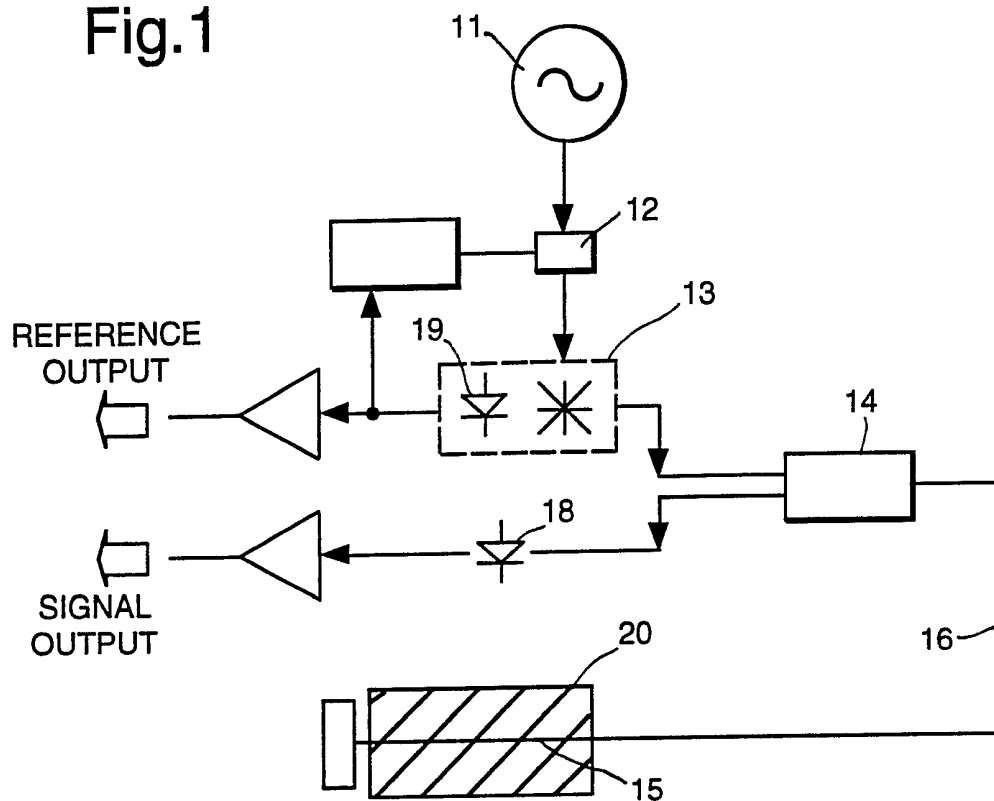


Fig.3

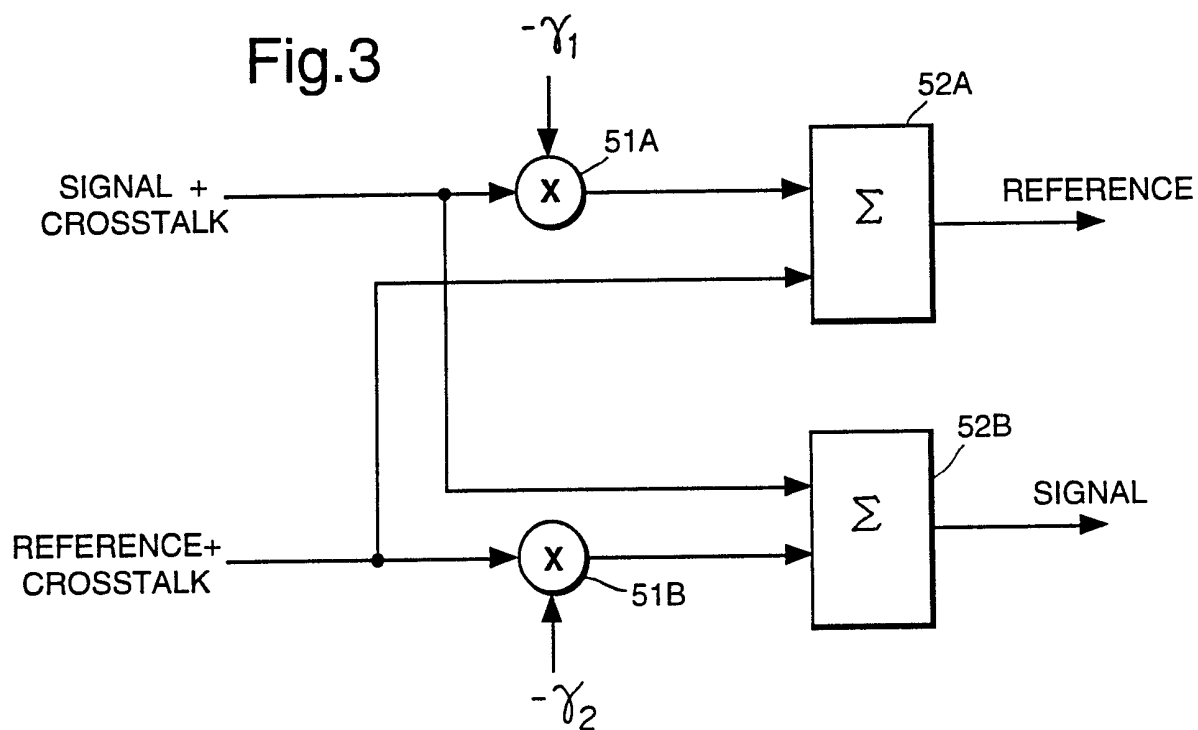


Fig.2

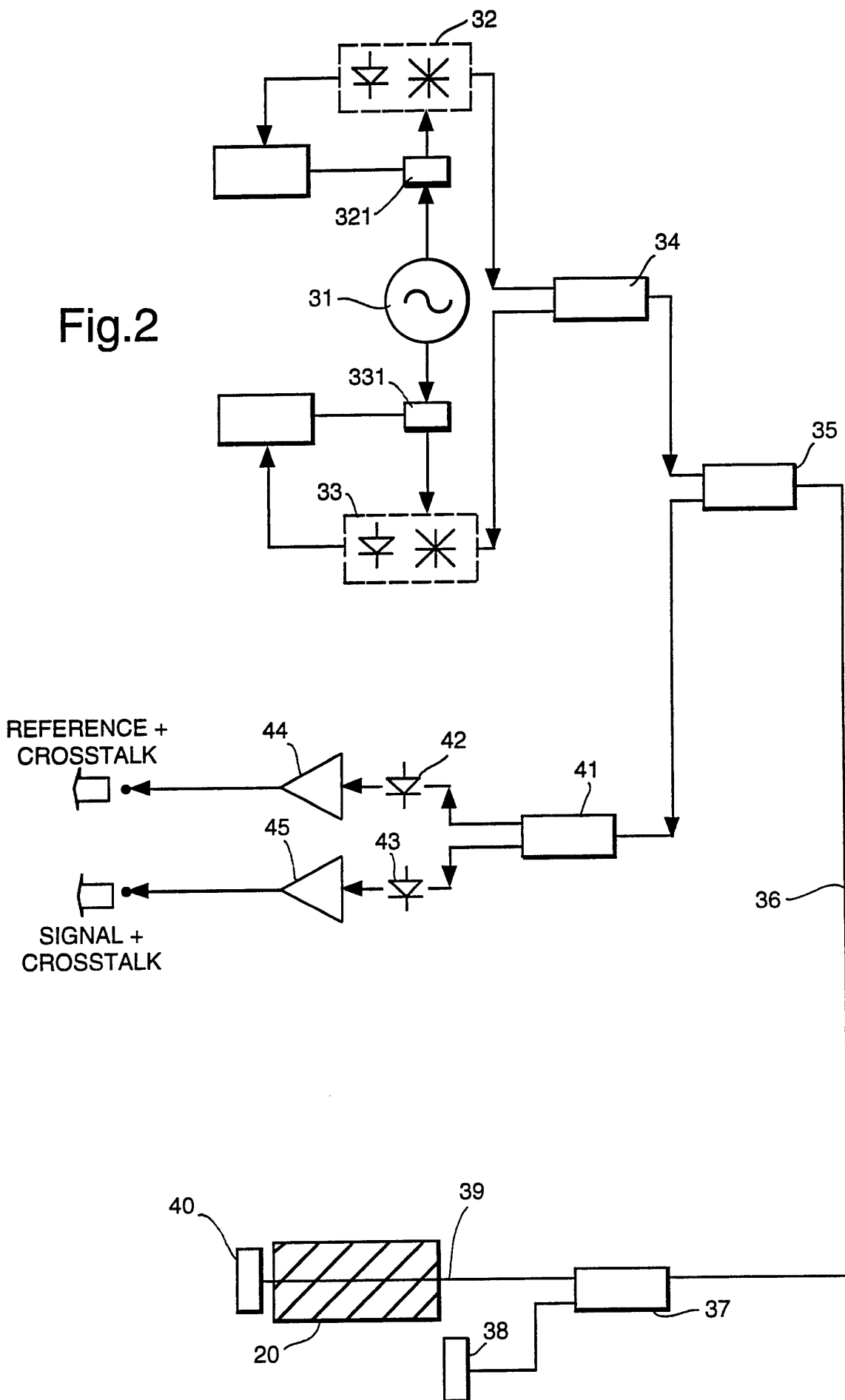
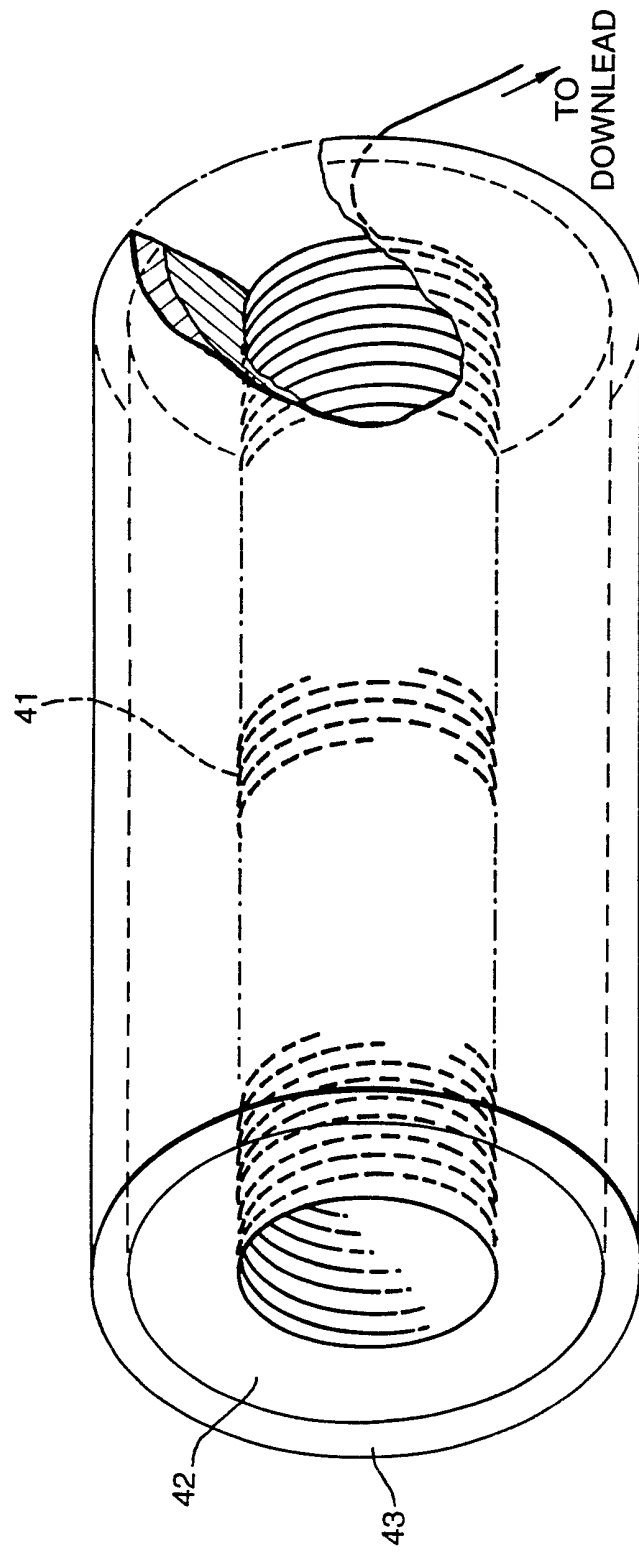


Fig.4.



OPTICAL FIBRE STRAIN SENSOR

This invention relates to optical fibre strain sensors, and in particular to a strain sensor arrangement for monitoring the condition of a solid body subject to ageing.

It has been found that solid propellant bodies e.g. for missile rocket motors are subject to ageing during their service lifetime prior to use or destruction. This ageing results in shrinkage and cracking of the propellant body. Damage of this type may not be discovered until the missile is fired with the result that the rocket motor may fail to function properly. In extreme cases the launch platform may be destroyed. This problem may be mitigated by periodic visual inspection but this may not be convenient or even possible particularly under emergency conditions.

One approach to this problem that has been proposed is the provision of an optical fibre in contact with a surface of the propellant body. Monitoring strain in the fibre over a period of time can reveal dimensional change in the body resulting from ageing effects. The measurement of strain induced in an optical fibre has been demonstrated in a number of laboratories by means of a radio frequency (r.f.) interferometer superimposed on an optical carrier propagating in the fibre. As strain in the fibre increases, so does the optical path length resulting in a proportionate change in the phase of the demodulated r.f. signal. However, strain in all sections of the fibre, including a downlead coupling to the sensor fibre will influence the r.f. phase equally. It is therefore desirable to employ a second channel for reference purposes to eliminate the effects of strain in any optical fibre other than the sense fibre. One method of implementing this reference channel involves the use of a second optical wavelength which is reflected from a point at the input to the sense fibre while the first wavelength travels through the sense fibre.

Combining and separating the two wavelength channels is performed by wavelength multiplexing couplers. Whereas both channels are then influenced equally by strains in the download, only the first wavelength is subject to strains in the sense fibre. Download sensitivity is thus eliminated and so the difference between the phase delays seen in the two channels is due to the strain in the sense fibre only.

Unfortunately, this dual-wavelength reference technique imposes severe constraints on the isolation of the optical wavelength multiplexing couplers, as any crosstalk between the two channels will distort the observed phase difference. In practice, optical wavelength multiplexing couplers of sufficient isolation are difficult to produce reliably, and high isolation is often only obtained at the expense of high back-reflection, which has a similar degrading effect on the phase measurement.

The object of the invention is to minimise or to overcome this disadvantage.

According to the invention there is provided an optical fibre strain sensor arrangement, including a sense fibre to which in use strain may be applied, a primary modulated optical source operating at a first wavelength, means for coupling the primary optical source to the sense fibre whereby to obtain a primary signal indicative of strain in the sense fibre, a reference optical source operating at a second wavelength and modulated identically to the primary source, the reference source being coupled to the coupling means whereby to provide a reference signal, means for summing weighted proportions of the primary and reference signals whereby to remove crosstalk and achieve substantially complete reproduction of the signals, and means for comparing the modulation phase of the separated primary and reference signals to obtain a measure of strain in the sense fibre.

The sensor arrangement provides a means of compensating for the effects of low optical isolation in the wavelength multiplexing coupler by the use of post optical detection signal processing thus sensing the necessity for high isolation. This allows the use of low-cost wavelength multiplexing couplers based on fused taper technology and having an inherently low-back reflection.

Embodiments of the invention will now be described with reference to the accompanying drawings in which:

Fig. 1 illustrates a typical optical fibre radio frequency interferometer sensor arrangement;

Fig 2 shows a dual wavelength sensor arrangement according to the invention;

Fig. 3 is a schematic diagram of a signal processor arrangement for use with the sensor arrangement of Fig. 2; and

Fig. 4 illustrates the application of a strain sense fibre to a rocket motor propellant body.

The configuration of a typical radio-frequency interferometer based on an optical fibre system is shown schematically in Fig. 1. Radio frequency modulation from a modulator 11 is imposed via a matching impetus 12 on an optical carrier by a laser 13 and passes through a coupler 14 to sense fibre 15 via a downlead 16. In use, the sense fibre will be in contact with a body 20 where surface condition is to be monitored for dimensional changes. After passing through the sense fibre 15, the light is reflected by a mirror 17 and returns via the sense fibre 15, the downlead 16 and the coupler 14 to a photodiode 18 where the radio frequency modulation signal is recovered. The laser output is monitored by a reference or monitor photodiode 19 whose output is amplified e.g. by a first transimpedance amplifier 21. The signal output of the photodiode is also amplified by a second transimpedance amplifier 22. The two amplifier outputs are compared whereby the phase of the sense fibre signal is compared to that of the reference signal obtained from the monitor photodiode 19 associated with the laser. Phase changes due to strain in the sense fibre result in changes in the phase difference between the signal and reference outputs. However, phase changes can also be caused by strains in the downlead 16 and these latter phase changes may mask those arising from the sense fibre 15.

Referring now to Fig. 2, there is shown a dual wavelength sensor arrangement according to the invention. In the arrangement of Fig. 2 a single radio-frequency modulator 31 drives first and second lasers 32, 33 each via a respective matching impedance 321, 331. The first laser 32 provides a signal source and the second laser 33, of different wavelength, provides a reference source. The modulated outputs of the two lasers are

fed via a first coupler 34 and a second coupler 35 to an optical downlead 36. The downlead is in turn coupled via a third, wavelength multiplexing, coupler 37 to a first mirror 38 providing a reference return signal and to a sense fibre 39, the latter being terminated by a second mirror 40 whereby to return the wanted signal. The returned signals, i.e. the wanted signal and the reference signal, from the downlead are fed via the coupler 35 to a fourth, wavelength multiplexing coupler 41 when the signal and reference wavelength components are separated and fed to respective photodiodes 42 and 43. The electrical outputs of the photodiodes are amplified by respective transimpedance amplifiers 44 and 45 to provide a signal output and a reference output. The returned reference signal is derived from a point close to the end of the sense fibre 39 and so also passes through the downlead. Strain on the downlead will therefore affect both reference and signal channels equally. The wavelength multiplexing coupler 37 at the input to the sense fibre ensures that only one wavelength traverses the sense fibre, the other being reflected from the mirror 38. This wavelength separation is repeated prior to detection so that the reference and signal channels are separately detected. Much of the optical path is therefore common to both reference and signal channels and so many sources of phase error are eliminated.

Nevertheless, the phase difference between the signal and reference outputs only reflects the true additional phase of the sense fibre if there is good separation of the wavelengths at the two wavelength multiplexing couplers. If this is not so, crosstalk between the two channels will occur, resulting in a distorted phase measurement. This crosstalk is substantially eliminated by the signal processing circuit of Fig. 3. The two signals, each including some crosstalk, are fed each to a respective multiplying mixer 51A, 51B, where each 'raw' signal is mixed with a respective weighting signal - γ_1 and - γ_2 . The derivation of these weighting signals will be described below. Each mixed signal is then summed with the other 'raw' signal in a respective summation circuit 52A, 52B. By appropriate choice of the weighting signals substantially complete separation to recover the wanted and reference signals can be achieved.

It is assumed that the system is substantially lossless, that equal power is emitted by the two lasers, and that the gains of the amplifiers are matched in the two channels. We also assume that the path length from the signal channel laser via the optical system, the sense fibre and the signal

$$\frac{(1-a)}{a}$$

at the wavelength multiplexing couplers at the sense fibre and

$$\frac{(1-\alpha)}{\alpha}$$

at the wavelength multiplexing couplers near the photodiodes. Similarly, let the isolation for the reference channel be

$$\frac{(1-b)}{b}$$

at the wavelength multiplexing couplers at the sense fibre and

$$\frac{(1-\beta)}{\beta}$$

at the wavelength multiplexing couplers near the photodiodes. Here a, b, α and β are the proportions of the optical power passing through the wavelength multiplexing couplers as intended, and $(1-a)$, $(1-b)$, $(1-\alpha)$ and $(1-\beta)$ are the proportions of the power leaking into the opposite channel. Ideally, of course, a, b, α and β would be equal to 1, giving total isolation.

The fractional signal channel output, S_1 , (so that, for perfect isolation, the output is unity) is given by

$$S_1 = \alpha [a^2 e^{j\phi} + (1-a)^2 e^{j\theta}] + (1-\beta) [b^2 e^{j\theta} + (1-b)^2 e^{j\phi}]$$

and similarly, the fractional reference channel output, S_2 , is given by

$$S_2 = \beta [b^2 e^{j\theta} + (1-b)^2 e^{j\phi}] + (1-\alpha) [a^2 e^{j\phi} + (1-a)^2 e^{j\theta}]$$

The powers of 2 arise because the wavelength multiplexing coupler at the sense fibre is traversed twice - out and return.

Rearranging gives

$$S_1 = [\alpha a^2 + (1 - \beta)(1 - b)^2]e^{j\phi} + [\alpha(1 - a)^2 + (1 - \beta)b^2]e^{j\phi}$$

and

$$S_2 = [\beta b^2 + (1 - \alpha)(1 - a)^2]e^{j\theta} + [\beta(1 - b)^2 + (1 - \alpha)a^2]e^{j\theta}$$

Then, performing the following operation

$$S_{sig} = S_1 - \gamma_1 S_2$$

where

$$\gamma_1 = \frac{[\alpha(1-a)^2 + (1-\beta)b^2]}{[\beta b^2 + (1-\alpha)(1-a)^2]}$$

removes the crosstalk contribution to the signal channel output, and so S_{sig} is dependent on the signal phase, ϕ , only. Similarly

$$S_{ref} = S_2 - \gamma_2 S_1$$

where

$$\gamma_2 = \frac{[\beta(1-b)^2 + (1-\alpha)a^2]}{[\alpha a^2 + (1-\beta)(1-b)^2]}$$

enables the reference phase θ to be recovered because S_{ref} is independent of the signal phase.

This algorithm can be readily modified to allow for system losses by multiplying the terms a , b , α and β , $(1-\alpha)$, $(1-\beta)$, $1-\alpha$ and $(1-\beta)$ by the insertion loss appropriate to the respective path through the wavelength multiplexing coupler. A similar correction term can be used to allow for an imbalance in the power produced by the two lasers or the gains of the amplifiers in the two channels. Hence, the signal channel output, S_1 , becomes

$$S_1 = A_{sig}(S_{sig}S_1\alpha[S_2a^2e^{j\phi} + S_3(1-a)^2e^{j\theta}] + S_{ref}r_4(1-\beta)[r_2b^2e^{j\theta} + r_3(1-b)^2e^{j\phi}])$$

and similarly the reference channel output, S_2 , becomes

$$S_2 = A_{ref}(S_{ref}r_1\beta[r_2b^2e^{j\theta} + r_3(1-b)^2e^{j\phi}] + S_{sig}s_4(1-\alpha)[s_2a^2e^{j\phi} + s_3(1-a)^2e^{j\theta}])$$

where: A_{sig}, A_{ref} are the gains of the signal and reference channel amplifiers combined with their respective photodetectors;
 S_{sig}, S_{ref} are respectively, the signal and reference channel laser output powers;
 S_i, r_i are additional losses in the optical circuit, over and above the effects of wavelength multiplexing coupler isolation, for the signal and reference wavelengths respectively.

γ_1 and γ_2 then become

$$\gamma_1 = \frac{A_{sig}([S_{sig}s_1\alpha s_3(1-a)^2 + S_{ref}r_4(1-\beta)r_2b^2])}{A_{ref}([S_{ref}r_1\beta r_2b^2 + S_{sig}s_4(1-\alpha)s_3(1-a)^2])}$$

$$\gamma_2 = \frac{A_{ref}([S_{ref}r_1\beta r_3(1-b)^2 + S_{sig}s_4(1-\alpha)s_2a^2])}{A_{sig}([S_{sig}s_1\alpha s_2a^2 + S_{ref}r_4(1-\beta)r_3(1-b)^2])}$$

An implementation of the algorithm is shown schematically in this signal process arrangement of Fig. 3. The "signal + crosstalk" and "reference + crosstalk" at the left of the diagram represent the signal output and reference output, respectively, shown in Fig. 2. The signal and reference at the right of Fig. 3 represent the corrected outputs.

The operation may be carried out using analogue components, such as analogue multipliers and linear amplifiers, in which case the phase angle difference between the phase angles θ . and ϕ , of the reference and signal channels respectively, is then obtained by inputting both signals into a standard vector voltmeter.

Alternatively, the operation may be performed digitally by sampling the input signals ("signal + crosstalk" and "reference + crosstalk", Fig. 3) and

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Alternatively, the operation may be performed digitally by sampling the input signals ("signal + crosstalk" and "reference + crosstalk", Fig. 3) and then carrying out the computation using a digital processor or a computer to obtain the phase angle difference.

Fig. 4 shows the manner in which a sense fibre 41 may be applied to a generally tubular propelled body 42 contained within a motor casing 42. The fibre 14, which is typically about 30m in length is wound as a helix on the inner surface of the propellant body 43. The fibre 41 may be embedded in the surface of the body 42.

The optimum position of the fibre within the motor will depend upon the motor structure and geometry and upon where the strain is desired to be measured. The arrangement shown in Fig. 4 is suitable for measuring strains induced by differential thermal expansion within the propellant. Alternatively, the fibre could be wound just inside the casing where debonding of the propellant from the case and deformation of the casing could be detected.

When the fibre is subject to strain a change in optical length results and hence a change in the phase of the modulation signal returned from the embedded fibre.

Several such sensors may be multiplexed together, for instance by having multiple semi-reflective mirrors spaced at intervals along the fibre and separating the returned signals using optical time domain reflectometry, to provide improved spatial resolution of the strain distribution in the motor.

CLAIMS

1. An optical fibre strain sensor arrangement, including a sense fibre to which in use strain may be applied, a primary modulated optical source operating at a first wavelength, means for coupling the primary optical source to the sense fibre whereby to obtain a primary signal indicative of strain in the sense fibre, a reference optical source operating at a second wavelength and modulated identically to the primary source, the reference source being coupled to the coupling means whereby to provide a reference signal, means for summing weighted proportions of the primary and reference signals whereby to remove crosstalk and achieve substantially complete reproduction of the signals, and means for comparing the modulation phase of the separated primary and reference signals to obtain a measure of strain in the sense fibre.
2. An optical fibre strain sensor as claimed in claim 1, wherein the sense fibre is terminated by first reflecting means from the primary signal and the coupling means is associated with second reflecting means from the reference signal.
3. A optical fibre strain sensor as claimed in claim 1 or claim 2, wherein said modulation is derived from a radio-frequency source.
4. An optical fibre strain sensor as claimed in claim 1, 2 or 3, wherein each said optical source comprises a laser.
5. An optical fibre strain source substantially as described herein with reference to and as shown in Figs. 2 and 3 of the accompanying drawings.
6. A solid propellant body provided with a strain sensor as claimed in any one of the preceding claims.

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Examiner's report to the Comptroller under
Section 17 (The Search Report)

Application number 9402447.8

Relevant Technical fields

(i) UK Cl (Edition M) G1A (ACEW)

(ii) Int Cl (Edition 5) G01L

Databases (see over)

(i) UK Patent Office

(ii) On_line databases: WPI, WPIL

Search Examiner

T BERRY

Date of Search

21 MARCH 1994

Documents considered relevant following a search in respect of claims 1 to 6

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
	NONE	

Category	Identity of document and relevant passages	Relevant to claim(s)

Categories of documents

X: Document indicating lack of novelty or of inventive step.

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