A strain sensor uses optical fibers including strain insensitive portions and a strain sensitive portion. The optical fibers form a sensitive arm of an optical phase locked loop (OPLL). The use of the OPLL allows for multimode optical fiber to be used in a strain insensitive configuration. Only strain information for the strain sensitive portion is monitored rather than the integrated strain measurements commonly made with optical fiber sensors.
FIG. 1

\[ \delta \phi_n = 0 \]

\[ \delta \phi_n \neq 0 \]
STRAIN INSENSITIVE OPTICAL PHASE LOCKED LOOP

BACKGROUND OF THE INVENTION

The invention described herein was jointly made by an employee of the United States Government and a contract employee during the performance of work under NASA Contract No. NAS-1-19236. In accordance with 35 U.S.C. 202, the contractor elected not to retain title.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a drawing showing a fiber having a strain sensitive region and strain insensitive regions of the fiber carrying an optical signal to and from the strain sensitive region.

FIG. 2 is a drawing showing a system according to the present invention in an OPLL configuration.

DESCRIPTION OF PREFERRED EMBODIMENTS

Refracting first to FIG. 1, a multimode optical fiber sensor is shown. The multimode optical fiber sensor 2 is made up of a strain insensitive fiber 4 leading to a strain sensitive fiber 6 located in the region being monitored and a second strain insensitive fiber 8 leading away from the strain sensitive fiber. For example the three fibers may be connected by splicing. Light 1 enters the sensor and strain 3 is applied.

A voltage controlled oscillator 10 is used to directly modulate a laser 12 and to provide a reference signal to a
double balanced mixer 14, as shown in FIG. 2. The laser radiation passes through a multimode optical fiber sensor 2.

The second strain insensitive fiber 8 leads to a detector 16. The detected signal passes through an amplifier 18, the amplified signal passes through the mixer 14 and is mixed with the reference signal. The phases of the two signals are maintained at quadrature by feedback of the DC error voltage from the mixer 14 to the oscillator 10. A filter 22 removes the radio frequency component coming from the mixer 14.

A change in the phase of the modulation is expressed as an error voltage at the mixer 14 and is compensated by a change in the modulation frequency. A change in phase length, $\Delta \phi$, of the optical fiber will produce a change in frequency, $\Delta F$, according to:

$$\frac{\Delta \phi}{L} = -\frac{\Delta F}{P}$$  \hspace{1cm} (1)

Where $L$ is the effective path length of the strain sensitive fiber and $P$ is the nominal frequency value. Frequency is monitored by a counter 24.

An important consideration is the strain insensitive optical fibers 4 and 8. The phase shift due to strain in the OPLL is given by:

$$\delta \phi = \frac{V_p \sigma}{c L} (S_{\text{eff}} + P_{\text{eff}} n_{\text{core}}^2)$$  \hspace{1cm} (2)

$$F_{\text{eff}} = \frac{P_{12} - \gamma (P_{11} + P_{12})}{2}$$  \hspace{1cm} (3)

Where $P_{11}$ and $P_{12}$ are the strain optic coefficients of the fiber, $V_p$ is the Poisson's ratio of the fiber, $\omega$ is the frequency of modulation of the laser, $c$ is the speed of light, $z$ is the length of the fiber under strain, $S_{\text{eff}}$ is the value of axial strain and $n_{\text{core}}$ is the refractive index of the fiber core. The fiber is assumed to be weakly guiding, that is, it meets the inequality:

$$\frac{n_{\text{core}} - n_{\text{clad}}}{2n_{\text{core}}} \leq 0.01$$  \hspace{1cm} (4)

From the above, it is evident that a fiber can be made more or less sensitive by choosing appropriate optical fiber parameters. So, for a strain insensitive fiber, the core refractive index must be given by:

$$n_{\text{core}} = \sqrt{\frac{2}{P_{\text{eff}}}}$$  \hspace{1cm} (5)

While for strain sensitive fiber it is best to maximize Eqn. 2.

Using appropriate parameters in Eqn. 5 it is determined that a strain insensitive fiber is one with a very high core refractive index, e.g. $n_{\text{core}} = 4.5$. Germanium, for example is an appropriate material for producing multimode optical fibers with very high refractive index.

Other variations and uses will be apparent to those skilled in the art. The above embodiments are not exhaustive but rather are given by way of example. It is understood that the present invention is capable of numerous modifications within the scope of the following claims.

We claim:
1. A strain sensor comprising: an optical phase locked loop comprising a strain sensitive arm; the strain sensitive arm of the optical phase locked loop comprising: a strain sensitive, multimode optical fiber, and at least one strain insensitive, multimode optical fiber disposed to transmit light passing through said strain sensitive, multimode optical fiber.
2. A strain sensor as recited in claim 1 wherein the strain insensitive, multimode optical fiber is chosen to have a core refractive index given by the equation:

$$n_{\text{core}} = \sqrt{\frac{2}{P_{\text{eff}}}}$$

where $P_{\text{eff}}$ is the effective strain optical coefficient of the fiber and $n_{\text{core}}$ is the refractive index of the fiber core.
3. A strain sensor as recited in claim 1 wherein the strain sensitive, multimode optical fiber is chosen to have a core refractive index determined by maximizing the equation:

$$\delta \phi_{\text{in}} = \frac{V_p \sigma}{c L} (S_{\text{eff}} + P_{\text{eff}} n_{\text{core}}^2)$$

where $\delta \phi_{\text{in}}$ is a phase shift due to strain, $\omega$ equals frequency of modulation of a laser, $c$ equals speed of light, $z$ equals length of the fiber under strain, $S_{\text{eff}}$ equals value of axial strain, $n_{\text{core}}$ is the core refractive index, and $P_{\text{eff}}$ is the effective strain optical coefficient of the fiber.
4. A strain sensor as recited in claim 1 wherein the optical phase locked loop further comprises: light producing means for injecting light into the strain insensitive, multimode optical fiber; detecting means positioned to accept light that has passed through the strain sensitive, multimode optical fiber; means for controlling the light producing means in a phase locked, frequency modulating, feedback arrangement; and, means for monitoring a change in modulating frequency, indicating strain in the strain sensitive, multimode optical fiber; the means for controlling the light producing means in a phase locked, frequency modulating, feedback arrangement comprising: an amplifier, for amplifying a signal from the detecting means; a voltage controlled oscillator, the voltage controlled oscillator directly controlling the light producing means, and further providing a reference signal; a mixer, mixing output from the amplifier with the reference signal and producing a mixed output signal; a filter, removing a radio frequency noise component from the mixed output signal and producing a filtered, mixed signal; and the filtered, mixed signal controlling the voltage controlled oscillator.

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