A strain sensor is constructed from a two mode optical fiber. When the optical fiber is surface mounted in a straight line and the object to which the optical fiber is mounted is subjected to strain within a predetermined range, the light intensity at any point at the output of the optical fiber will have a linear relationship to strain, provided the following equation is less than 0.17 radians:

\[ \delta \phi_0 - \delta \phi_1 = \frac{\Delta kL S_1}{\nu^2} \sum_{n=0}^{\infty} \left( -1 \right)^n \frac{\nu L}{2 \pi n \eta_0} \left( 1 + 2 \eta_0 \nu - (3 - 4 \eta_0) \nu^2 \right) \left( \frac{\eta_0 \nu}{\nu - (3 - 4 \eta_0) \nu^2} \right) \]

where \( n_0 \) represents the refractive index of the core, \( k \) represents the wavenumber of the light, \( L \) represents the length of the optical fiber, \( S_1 \) represents axial strain, \( \nu \) is a solution to the eigenvalue equation of the optical fiber, \( \nu \) represents the Poisson ratio, \( P_e \) represents the effective strain-optic coefficient of the optical fiber and \( n_{\text{eff}} \) represents

\[ K_1^2 = K_1 + Ki_{-1} \]

where \( K_1 \) is the modified Bessel function of second kind of order with argument given by

\[ W_{\eta_0} = \sqrt{\nu^2 - U_{\eta_0}^2} \]

where

\[ V = ak \sqrt{\nu_0^2 - \nu_{\text{eff}}^2} \cdot L \]

4 Claims, 1 Drawing Sheet
OPTICAL FIBER STRAIN SENSOR WITH IMPROVED LINEARITY RANGE

CROSS-REFERENCE TO RELATED APPLICATION

This application is related to the following U.S. patent application filed on the same date and assigned to the same assignee by the same inventors: DISCRETE OPTICAL FIBER STRAIN SENSOR which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed to an optical fiber strain sensor and, more particularly, to an optical fiber strain sensor in which received light intensity changes linearly with respect to strain over a relatively wide range of strain.

2. Description of the Related Art

A known technique for measuring strain is to use the light transmitted by an optical fiber affixed to an object under strain. Conventionally, the modal pattern produced by light at the receiving end of an optical fiber under strain is monitored to detect changes in the modal pattern. The changes in the pattern are caused by changes in the index of refraction n and the propagation constants of each fiber mode. As a result, the modal phase term, \( \beta_{n}\text{z,} \) of the electric field is shifted by an amount \( \delta \beta \). This phase shift phenomenon has been theoretically studied and experimentally used in applications that involve determination of strain using single mode, few mode and multimode fibers.

A single mode fiber is the simplest kind of strain sensor using optical fibers. It is basically an interferometer that compares the modal phase shift of two fibers: one fiber is subjected to strain and the other serves as a reference. Such a device is described in "Fiber Optics Sensors" by Sirkis et al. in Applied Optics, vol. 17, pages 2867-2869, September 1978, for surface mounted sensors using "weakly guiding" optical fibers. Another example of strain sensors using weakly guiding optical fibers was described in "Complete Phase-Strain Model for Structurally Embedded Interferometric Optical Fiber Sensors" by Sirkis et al. in Journal of Intelligent Material Systems and Structures, vol. 2, pages 3-24 (1991). The latter paper describes both surface mounted and embedded sensors in many strain field configurations.

There are several drawbacks to optical fiber strain sensors using known techniques. First, the phenomenon has only begun to be investigated and the theoretical underpinnings are not fully understood. Second, the shifting of patterns can be complex and requires either an intelligent detector, or careful alignment of a detector with a pattern produced for a given amount of strain. Third, strain is measured over the entire length of the optical fiber with the result that it is difficult to mount an optical strain sensor to measure strain at a discrete location.

SUMMARY OF THE INVENTION

An object of the present invention is to provide an optical fiber strain sensor which measures strain easily. The above object is attained by providing a strain sensor, comprising: a two-mode optical fiber constructed of materials producing an intermodal phase difference \( \delta \Phi_{01-011} \) of 0.17 radians when subjected to stress within a measurable range of the strain sensor; light supply means for supplying light to a first end of the optical fiber; and light intensity detection means for detecting light intensity of a point at a second end of the optical fiber. The optical fiber may be a single mode, two mode or multi-mode fiber. The light intensity detection means may be a conventional photodiode or other light sensitive electronic device for converting the light intensity to an electrical signal, coupled with means for transmitting the light emerging from the point at the second end of the optical fiber to the photodiode or other device. The means for transporting may be a lens, an optical fiber not subjected to strain, or a strain insensitive optical fiber as disclosed in the corresponding patent application.

These objects, together with other objects and advantages which will be subsequently apparent, reside in the details of construction and operation as more fully hereinafter described and claimed, reference being had to the accompanying drawings forming a part hereof, wherein like reference numerals refer to like parts throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a strain sensor according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

For a surface mounted straight circular optical fiber having a step index profile which is under axial strain, the normalized phase difference, \( \delta \Phi / k L S_{1} \) is defined as

\[
\frac{\delta \Phi_{01}}{k L S_{1}} = \frac{\beta_{01}}{k} + \left( \frac{\mathcal{T}_{01}^{2}}{2} - \beta_{n}^{2} \right) \frac{P_{df}}{k} - \frac{n_{b} \mathcal{P}_{01}}{k} \left( (v\gamma_{1} + \gamma_{2} \alpha_{1}) P_{df} \right),
\]

where \( P_{df} \) is defined as the effective strain-optic coefficient or

\[
P_{df} = \frac{P_{12} - v(P_{11} + P_{12})}{2},
\]

\[
\eta_{b} = \frac{K_{2}}{K_{1}-1},
\]

\( \beta_{01} \) is the propagation constant of a mode of order/and rank \( n, \) \( U_{in} \) is solution to the eigenvalue equation of a weakly guiding fiber, \( n_{co} \) and \( n_{cla} \) are the refractive indices of the core and cladding respectively, \( a \) is the core radius, \( L \) is the length of the fiber which is under stress, \( S_{1} \) is the value of the axial strain, \( P_{11} \) and \( P_{12} \) are the strain optic coefficient, \( v\gamma_{1} \) is the Poisson ratio and \( K_{i} \) is the modified Bessel function of second kind of order \( i \) with argument given by

\[
\mathcal{W}_{in} = \sqrt{\nu^{2} - c_{in}^{2}},
\]

where
domain sensors for measuring strain. In order to determine the strain in the fiber, the intensity of the fiber's normalized phase shift can be written as a proportionality. Further, since numerous modifications and changes will fall within the true spirit and scope of the invention. We claim:

1. A strain sensor, comprising:
   a two-mode optical fiber constructed of materials producing an intermodal phase difference of less than 0.17 radians when subjected to stress within a measurable range of the strain sensor; light supply means for supplying light to a first end of said optical fiber; and light intensity detection means for detecting light intensity of the point at a second end of said optical fiber.

2. A strain sensor as recited in claim 1, wherein said light intensity detection means comprises:
   a) conversion means for converting the light intensity to an electrical signal; and
   b) means for transporting light emerging from the point at the second end of said optical fiber to said conversion means.

3. A strain sensor as recited in claim 1, wherein said optical fiber is constructed of material which when
subjected to strain within a predetermined range has characteristic parameters for $\delta \phi_{01}-\delta \phi_{11}$ to be less than 0.17 radians when defined as

$$\delta \phi_{01} - \delta \phi_{11} =$$

$$\frac{n_{co} \Delta M S_1}{\mu^2} \sum_{l=0}^{\infty} (-1)^{l+1} U_l^0(1 + 2\eta_1) \gamma - (3 - 4\eta_1) k_{01}^2 P_{ef}$$

where $n_{co}$ represents the refractive index of the core, $k$ represents the wavenumber of the light, $L$ represents the length of said optical fiber, $S_1$ represents axial strain, $V$ is

$$\sqrt{\kappa} \sqrt{\pi_{co}^2 - \pi_{dco}^2} .$$

$U$ is a solution to the eigenvalue equation of said optical fiber, $\nu$ represents the Poisson ratio, $P_{ef}$ represents the effective strain-optic coefficient of said optical fiber and $n_{in}$ represents

$$\eta_{in} = \frac{K_l^2}{K_{l+1}K_{l-1}} .$$

where $K_l$ is the modified Bessel function of second kind of order/with argument given by

$$w_{ce} = \sqrt{\nu^2 - U_{in}^2} ,$$

where

$$V = \kappa \kappa \sqrt{\pi_{co}^2 - \pi_{dco}^2} .$$

4. A strain sensor, comprising:

- a single mode optical fiber constructed of materials producing a phase of a fundamental mode $\delta \phi_{01}$ of less than 0.17 radians when subjected to stress within a measurable range of the strain sensor;
- light supply means for supplying light to a first end of said optical fiber; and
- light intensity detection means for detecting light intensity of the point at a second end of said optical fiber.