A Fiber-Optic Temperature Sensor Based on LP\textsubscript{01} – LP\textsubscript{02} Mode Interference

Arun Kumar, Rajeev Jindal, Ravi K. Varshney, and Sangeet K. Sharma

Department of Physics, Indian Institute of Technology, Hauz Khas, New Delhi 110 016, India

Received April 20, 1999

We studied a fiber-optic temperature sensor based on the interference between LP\textsubscript{01} and LP\textsubscript{02} modes of a circularly symmetric few mode fiber. Theoretical analysis predicting the sensitivity of such a sensor is presented; the predictions are in excellent agreement with the experimentally measured value. A simple scheme for practical implementation of such a sensor is also suggested. The proposed sensor should be easier to implement than the existing two-mode fiber sensors using elliptical-core fibers.

INTRODUCTION

Optical fibers are increasingly being used to realize novel fiber-optic sensors. The high sensitivity of optical fibers to external perturbation and their immunity to electromagnetic interference make them a good candidate for the same. The most sensitive fiber-optic sensors are based on the phase modulation of the propagating light by the physical parameter to be sensed and use two single-mode fibers forming Mach–Zehnder or Michelson interferometric arrangements [1]. However, in such sensors, the reference and the sensing arms are physically at different locations and hence even a small relative change between the two arms in the ambient conditions (such as temperature) can affect the output of the sensor drastically. This problem is solved to its maximum extent in fiber-optic modal sensors where two modes of one fiber act as two arms of the interferometer.

The modal sensors reported in the literature are based on interference between the first two (LP\textsubscript{01} and LP\textsubscript{11}\textsuperscript{even}) modes of a fiber. The feasibility of practical implementation of these sensors using circular-core fibers, however, is obstructed by the two possible lobe orientations of the second-order mode [2] resulting in an unstable sensor. In order to overcome this problem such sensors use highly elliptical core (e-core) fibers [3, 4]. In the practical implementation of such sensors
a single-mode e-core fiber is spliced at the input end of the sensing fiber as the lead-in fiber and a single-mode circular-core fiber as the lead-out fiber [5]; at the input end to excite both the modes in the sensing fiber equally and at the output end to pick up equal amount of contributions from the LP_{01} and LP_{11}^{even} modes. The lead-in and lead-out fibers have to be spliced along the major axis of the core ellipse with a predetermined offset, which is a difficult task. Further, elliptical core fibers are costly and are more lossy.

In the present paper we propose a modal sensor based on the interference between the first two circularly symmetric (LP_{01} and LP_{02}) modes of a few-mode circular-core fiber. The proposed sensor can be realised using a commonly available single mode fiber optimized at 1.31 μm operating at lower wavelength (0.6328 μm). In Ref. [2, 6] the authors have examined patterns resulting from the interference of various modes of a few mode fiber. However, to the best of our knowledge, no study has been yet reported on a sensor based on the interference between LP_{01} and LP_{02} modes. We first give a simple theoretical analysis for calculating the temperature sensitivity of such a sensor. We then report an experiment which has been carried out to show the working of such a sensor and to measure the temperature sensitivity. The experimentally measured value of the temperature sensitivity is found to be in excellent agreement with the theory.

THEORETICAL ANALYSIS

β_1 and β_2 represent the propagation constants of the LP_{01} and LP_{02} modes and L is the length of the sensing fiber. The phase difference developed between the two modes at the output end of the sensing fiber is given by

\[ \Delta \Phi = \Delta \beta \cdot L, \]  

where \( \Delta \beta = \beta_1 - \beta_2 \). The temperature sensitivity, \( \eta \), defined as the rate of change of \( \Delta \Phi \) with respect to temperature per unit length of the sensing fiber, will be given by

\[ \eta = \frac{1}{L} \frac{\partial (\Delta \Phi)}{\partial T} = \frac{\partial (\Delta \beta)}{\partial T} \frac{1}{L} \frac{\partial L}{\partial T} + (\Delta \beta) \frac{1}{L} \frac{\partial L}{\partial T}. \]  

In the present analysis we assume that the core and cladding both have the same thermal expansion coefficient (\( \alpha \)) and the same thermo-optic coefficient (\( \tau \)), which are defined as

\[ \alpha = \frac{1}{L} \frac{\partial L}{\partial T} = \frac{1}{a} \frac{\partial a}{\partial T} \]  

and

\[ \tau = \frac{1}{n_j} \frac{\partial n_j}{\partial T}, \quad j = 1, 2, \]  

where \( n_j \) is the refractive index of the mode at temperature \( T \).
where \( a \) represents the core radius; \( n_1, n_2 \) are the refractive indices of core and cladding, respectively.

In order to calculate \( \partial(\Delta \beta)/\partial T \) we use the expression

\[
\beta_i^2 = k_0^2 \left[ n_i^2 + b_j (n_i^2 - n_z^2) \right]
\]  

(5)

where, \( b_j = (\beta_i^2 - k_0^2 n_z^2)/k_0^2(n_i^2 - n_z^2) \) represents the normalized propagation constant and \( k_0 \) is the free space wavenumber.

Differentiating Eq. (5) with respect to \( T \) gives

\[
2 \beta_j \frac{\partial \beta_j}{\partial T} = k_0^2 \left[ 2n_i \frac{\partial n_z}{\partial T} + \frac{\partial b_j}{\partial T}(n_i^2 - n_z^2) + b_j \left( 2n_i \frac{\partial n_1}{\partial T} - 2n_z \frac{\partial n_z}{\partial T} \right) \right]
\]

\[
- k_0^2 \left[ 2n_i^2 \tau + \frac{\partial b_j}{\partial T}(n_i^2 - n_z^2) + 2b_j (n_i^2 - n_z^2) \tau \right] \quad \text{[Using Eq. (4)]}
\]

\[
\Rightarrow \frac{\partial \beta_j}{\partial T} = \tau \beta_j + k_0^2 (n_i^2 - n_z^2) \frac{1}{2 \beta_j} \cdot \frac{\partial b_j}{\partial T}.
\]

Since \( b \) is a function of \( V \)-parameter of the fiber (= \( k_0 a \sqrt{n_i^2 - n_z^2} \)) only, one can write the above equation as

\[
\frac{\partial \beta_j}{\partial T} = \tau \beta_j + k_0^2 (n_i^2 - n_z^2) \frac{1}{2 \beta_j} \cdot \frac{\partial b_j}{\partial V} \frac{\partial V}{\partial T}.
\]  

(6)

where

\[
\frac{\partial V}{\partial T} = \frac{\partial}{\partial T} \left( k_0 a \sqrt{n_i^2 - n_z^2} \right)
\]

\[
= k_0 \cdot \frac{\partial a}{\partial T} \cdot \sqrt{n_i^2 - n_z^2} + k_0 a \cdot \frac{1}{2 \sqrt{n_i^2 - n_z^2}} \left( 2n_i \frac{\partial n_1}{\partial T} - 2n_z \frac{\partial n_z}{\partial T} \right)
\]

\[
= k_0 a \sqrt{n_i^2 - n_z^2} \left( \frac{1}{a} \frac{\partial a}{\partial T} \right) + k_0 a \cdot \frac{2}{2 \sqrt{n_i^2 - n_z^2}} \left( n_i \frac{\partial n_1}{\partial T} - n_z \frac{\partial n_z}{\partial T} \right)
\]

\[
= V(\alpha + \tau).
\]  

(7)

Using Eqs. (6) and (7) it can be easily shown that

\[
\frac{\partial (\Delta \beta)}{\partial T} = \frac{\partial (\beta_1 - \beta_2)}{\partial T}
\]

\[
= \tau (\beta_1 - \beta_2) + \frac{k_0^2 (n_i^2 - n_z^2)}{2} \cdot V(\alpha + \tau) \left\{ \frac{1}{\beta_1} \cdot \frac{\partial b_1}{\partial V} - \frac{1}{\beta_2} \cdot \frac{\partial b_2}{\partial V} \right\}.
\]  

(8)
The temperature sensitivity ($\eta$) of the sensor is thus given by

$$
\eta = \frac{1}{L} \frac{\partial (\Delta \Phi)}{\partial T} = (\tau + \omega) \left( \beta_1 - \beta_2 \right) + \frac{k_0^2 (n_1^2 - n_2^2)}{2} \cdot V \cdot \left\{ \frac{1}{\beta_1} \cdot \frac{\partial b_1}{\partial V} - \frac{1}{\beta_2} \cdot \frac{\partial b_2}{\partial V} \right\} .
$$

Values of $\partial b_1/\partial V$ and $\partial b_2/\partial V$ can be calculated using the universal $b$ vs $V$ curves.

**EXPERIMENTAL**

In order to demonstrate the working principle and to measure the temperature sensitivity of the proposed sensor we take a fiber which is single-moded at $\lambda = 1.31 \ \mu m$. The $V$-value and $\Delta$ of this fiber were estimated using the far-field measurement technique [7] at $\lambda = 1.31 \ \mu m$, which predicts $V = 2.4005$ and $\Delta = 0.0032$. At $\lambda = 0.6328 \ \mu m$, the fiber's $V$-number becomes 5.005 and it will support four modes, namely L$\text{P}_{00}$, L$\text{P}_{11}$, L$\text{P}_{21}$, and L$\text{P}_{02}$. Of these four modes, L$\text{P}_{01}$ and L$\text{P}_{02}$ are circularly symmetric and can be selectively excited if the light launched at the input end is axially symmetric. To achieve this we launched the light from a He–Ne laser ($\lambda = 0.6328 \ \mu m$) into the sensor fiber and adjusted the position of the focused spot to get the maximum coupling using an XYZ movement. A circularly symmetric Gaussian-like intensity pattern was observed at the output, indicating that most of the energy is coupled in the L$\text{P}_{01}$ mode. We then introduced an appropriate longitudinal offset between the focused spot and the input end of the fiber so that L$\text{P}_{01}$ and L$\text{P}_{02}$ modes were almost equally excited, as discussed below.

The fiber was heated by passing it through a heating arrangement (shown in Fig. 1) which consisted of a Constantan heating wire of suitable length wrapped on a quartz tube to provide a uniform temperature around a part of the fiber. The tube was surrounded by another quartz tube to prevent heat loss to the atmosphere. The

![Diagram](image-url)

**FIG. 1.** Experimental setup used to measure the temperature sensitivity of proposed sensor.
ambient temperature of the fiber was changed by changing the voltage across the heating wire through a power divider arrangement and the output of a detector placed at the center of the far-field pattern of the output was measured. The output power was observed to vary periodically with temperature. The input end of the fiber was now displaced longitudinally so that the depth of modulation of the output power vs temperature curve was maximized. In order to be sure that only LP$_{01}$ and LP$_{02}$ modes are excited we then scanned far-field intensity patterns at two different temperatures: when the intensity measured at the center of the pattern was maximum and minimum, respectively. The corresponding plots obtained on an X–Y recorder are shown in Figs. 2a and 2b; the symmetric nature of these curves indicates that only the circularly symmetric modes (LP$_{01}$ and LP$_{02}$) are excited. Figures 2a and 2b correspond to the two extreme cases of interference, namely when the LP$_{01}$ and LP$_{02}$ modes are (i) in phase and (ii) out of phase, respectively.

In order to measure the temperature sensitivity, the intensity variation with respect to the temperature of fiber was measured at the center of the far-field using a pin hole detector. This variation is shown in Fig. 3. One complete cycle in this intensity variation curve corresponds to a $2\pi$ change in phase difference between the two modes. Using these measurements, the change in temperature, $\Delta T_{2\pi}$, required to introduce a phase change of $2\pi$ was estimated to be $\Delta T_{2\pi} = 51^\circ\text{C}$.

The average temperature sensitivity ($\eta$) of the proposed sensor is then given by

$$\eta = \frac{1}{L} \cdot \frac{\partial (\Delta \Phi)}{\partial T} = \frac{2}{L(\Delta T)_{2\pi}}, \quad (10)$$

where $L$ is the fiber length exposed to the increase in the temperature, measured to be 23.3 cm. Substituting $\Delta T_{2\pi}$ and $L$ in Eq. (10), the experimental value of $\eta$ comes out to be

$$\eta_{exp} = 0.528 \text{ rad/}^\circ\text{C/m.} \quad (11)$$

**THEORETICAL CALCULATIONS**

Theoretical calculations were carried out to estimate $\eta$ theoretically using Eq. (9). The eigenvalue equation for LP$_{0m}$ modes was solved numerically, using the values of various parameters as $V = 5.005$, $n_2 = 1.4573$, $\Delta = 0.0032$, $\lambda = 0.6328 \mu\text{m}$, $\partial b_1/\partial V$ and $\partial b_2/\partial V$ were, 0.0565 and 0.237, respectively. Taking $\alpha = 5 \times 10^{-7} / ^\circ\text{C}$ and $\tau = 1 \times 10^{-5} / ^\circ\text{C}$, corresponding to fused silica [8], the theoretical value of the $\eta$ comes out to be (using Eq. (9))

$$\eta_{th} = -0.57 \text{ rad/}^\circ\text{C/m,} \quad (12)$$

which is in excellent agreement with the experimental result (see Eq. (11)). The negative sign represents that the change in phase of the LP$_{02}$ mode is larger than that of the LP$_{01}$ mode, which is expected.
FIG. 2. Far-field intensity plots when the $LP_{01}$ and $LP_{02}$ modes are (a) in phase, (b) out of phase; $x$ denotes the transverse distance and $I$ denotes the output intensity at the far field.
The proposed sensor can be implemented very easily in practice by splicing the two circular-core single mode (at $\lambda = 0.6328 \, \mu m$) fibers at both ends of the sensing fiber, having the same core diameter (125 $\mu m$). Light will then be launched into the SM fiber (at $\lambda = 0.6328 \, \mu m$), which will excite only the circularly symmetric modes in the sensing fiber. The parameters of the lead-in and lead-out fiber, however, should be selected in such a way that the overlap integrals of the LP_{01} and LP_{02} modes of the sensing fiber with the LP_{01} mode of the lead-in/lead-out fiber are almost equal. In that case the lead-in fiber will excite the LP_{01} and LP_{02} modes in the sensing fiber with almost equal power and the lead-out fiber will pick up almost equal powers from the two modes, resulting in a large modulation depth of the signal detected at the output of the lead-out fiber. A detailed theoretical study giving the design of the lead-in/lead-out and the sensor fiber for maximum sensitivity is under progress and will be reported separately.

CONCLUSION

In this paper we have studied a fiber-optic temperature sensor based on the interference of the LP_{01} and LP_{02} modes in a few-mode circular-core fiber. We have also carried out an experiment which verifies the proposed concept and the temperature sensitivity measured experimentally matches very well with the theoretically predicted value. A simple implementation scheme for such a sensor is also discussed. The proposed sensor should be less expensive and easier to implement than the existing two-mode fiber-optic sensors based on $e$-core fibers.

REFERENCES


