Distributed Strain Sensing Using Fiber Mode-Mode Interference

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ABSTRACT

A method based on interference between fundamental and higher order mode in birefringent fiber has been proposed for measuring strain distribution in cantilever beams. A frequency modulated optical signal from a laser diode was launched in a birefringent fiber whose 'V' number was set in the range 2.405-3.831. The beat signal produced due to the interference of two lower order modes LP_{01} and LP_{11} was detected in a photodetector. The change in propagation constants between two modes under loading conditions leads to a phase variation of interference signal. The amplitude of the beat frequency was measured in the frequency domain by varying the modulating frequency and it provides the measurand distribution along the beam. Results for strain distribution of a simply supported beam (51.0cm x 3.0cm x 0.6cm) for an applied load of 1000gm are presented.

Keywords: Distributed fiber sensor, Strain sensor, Modal interference.

1. INTRODUCTION

In recent years, a lot of interest has been created for fiber optic sensing of strain in concrete beam and advanced structures, as it provides real time and in situ measurement. Distributed fiber optic sensing has the ability of continuously monitoring the mechanical parameters of structures and this would allow the alleviating action to be taken in good time before any potentially damaging condition. Several different types of distributed fiber optic sensor have been reported for measuring strain in different structures and beams. Fiber Bragg grating sensors have been considered as promising tools for measuring strain in composite structures and beams [1, 2]. Distributed fiber sensors based on Brillouin scattering have been focused of great attention for measuring strain distribution in cantilever beams [3]. By analyzing the Brillouin back-scattered light power spectrum, the strain and the measurement position may be determined for a beam to which a concentrated load is applied. A quasi-distributed strain sensor based on built-in reflectors within the core of the optical fiber has been reported for measuring strain in a long structure [4]. A white light quasi-distributed fiber optic strain sensor based on a Mach- Zehnder optical path interrogator has been demonstrated to measure/ monitor strain distribution in smart structure [5]. To reduce the system cost, Michelson type quasi-distributed sensor has also been used to measure strain in plastic material, where an optical fiber ring provides the multiple reference waves for an array of serial connected strain sensor [6]. However, in these two beam interferometric sensors, the reference and sensing arms are placed at different locations, which can lead to error in measurement. In this paper, we report the use of modal interference in birefringent optical fiber for measuring strain in a simply supported beam. The beat frequencies produced due to the interference of LP_{01} and LP_{11} modes were measured using Fourier transform method. We investigate the strain distribution of an acrylic beam to which a concentrated load has been applied. By changing the modulating frequency the strain distribution has been obtained along the beam under loading conditions through the measurement of amplitude of the beat signals.

2. SENSOR PRINCIPLE

If the 'V' parameter of an optical fiber lies between 2.4048 and 3.8317, then LP01 and LP11 modes are guided in the fiber. The intensity pattern due to the interference of LP_{01} and LP_{11} modes may be written as [7],

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$$I(r,\phi) = A_{01}{}^2 f_{01}{}^2(r) + A_{11}{}^2 f_{11}{}^2(r)\cos^2\phi + 2A_{01}A_{11} f_{01}(r) f_{11}(r)\cos\phi\cos(\Delta\beta L - \Delta\theta) \qquad (1)$$

where r, ϕ are the radial coordinate and the azimuthal coordinate. A_{01} and A_{11} are the amplitude coefficients of the LP_{01} and LP_{11} modes respectively. The radial distribution functions f_{01} and f_{11} are given by

$$f_{01}(r) = \frac{V}{\pi a^2}\exp[-V(r/a)^2] \quad \text{, for the } LP_{01} \text{ mode}$$

$$f_{11}(r) = \frac{2}{\pi}\frac{V^2}{a^2}(r/a)^2\exp[-V(r/a)^2] \quad \text{, for the } LP_{11} \text{mode}$$

In the third term of (1), $\cos(\Delta\beta L - \Delta\theta)$ contributes towards the change in phase due to external perturbations, where $\Delta\beta = \beta_0 - \beta_1$, represents the change in propagation constants of LP_{01} (β_0) and LP_{11} (β_1) respectively, and $\Delta\theta = \theta_0 - \theta_1$. Whenever there is a change in external disturbance, $\cos(\Delta\beta L - \Delta\theta)$ will change due to the variation of $\Delta\beta L$ and accordingly intensity pattern will change, otherwise it remains constant.

A small perturbation due to strain at one point of the fiber causes a coupling of light to the other mode. The phase delay due to the different mode velocities leads to a beat frequency.

The interference pattern of LP_{01} and LP_{11} modes will vary due to the change in external perturbation.

We consider the distributed sensing system using FMCW technique in two mode fiber which offers large dynamic range and real time detection. If the frequency of a laser source is modulated by a current ramp, then instantaneous frequency can be written as [8]

$$\omega(t) = \omega_0 + \Omega t \qquad (2)$$

where ω_0 is the constant frequency and Ω is the modulation constant.

When mode conversion occurs at a distance L from the fiber end due to strain, the time difference between the modes LP_{01} and LP_{11} is,

$$\tau = (\beta_0 - \beta_1)L/\omega_0$$

$$\text{or} \qquad \tau = \lambda_0 L / cL_P \qquad (3)$$

where, beat length $L_P = 2\pi/(\beta_0 - \beta_1)$ and c is the velocity of light.

When the two beams interfere, the beat signal generated is,

$$S(t) = P_0\cos^2\theta + P_1\sin^2\theta + \sqrt{P_0P_1}\sin 2\theta|\gamma_{12}|\cos(\Delta\omega t + \Phi) \qquad (4)$$

where P_0 and P_1 are powers of LP_{01} and LP_{11} modes respectively, $\Delta\omega = \Omega\tau$ is the beat frequency, θ is the angle of orientation of polarizer at the detector end Φ is the phase difference between the two modes and γ_{12} is the complex degree of coherent. The term γ_{12} is a measure of the fringe contrast of the interference signal. For completely coherence beam of light, $|\gamma_{12}| = 1$ and for partially coherent beam, its value ranges $0 \le |\gamma_{12}| \le 1$. If the two beams are of equal intensity, the visibility or contrast of the fringe pattern $'V'$ becomes $V = |\gamma_{12}|$. Hence for good contrast of the pattern, source spectrum width should be narrow as it increases the coherence length of the source. The term Φ

determines the interference signal sensitivity. To make a sensitive interferometric sensor, the phase difference Φ between the two modes must be maximized under the external perturbation. Also, the finite spectral width of the source results the chromatic dispersion difference between the two modes. The maximum contrast of the pattern results when the paths traversed by the two modes are equal. However, the presence of chromatic dispersion due to finite spectral width of the source reduces the contrast. From the values of $\Delta\omega$, one can obtain the distance L, the point of disturbance, which is given by,

$$L = \frac{CL_P}{\lambda_0 \Omega} \Delta \omega \tag{5}$$

The beat frequencies carry the desired information about the measurand. The change in amplitude of the beat frequencies provides the value of the strain applied at the measurement position.

In our analysis, we consider a simply supported beam model where a concentrated load 'W' is applied at its center. If the fiber is attached at a distance 'Y' from the neutral axis in the direction of the beam length , then the strain distribution within elastic limit is given by

$$S(Z) = \frac{WY}{4EI'} Z \tag{6}$$

where Z is the distance from the left hand beam support, E is the elastic modulus and $I'$is the moment of inertia with respect to the neutral axis. As the strain is symmetric with respect to the center of the beam, the equation (6) provides the strain distribution for one half of the beam, maximum at the center while zero at the fixed end.

3. EXPERIMENT

Our experimental setup used for measurement of strain distribution is shown in fig.1. A single mode birefringent fiber (HB-800, Oxford Electronics) was attached to a simply supported beam (Acrylic rod) which was positioned at fiber length of 1.10 meter from the detector end. The dimension of the beam was 51.0cm x 3.0cm x 0.6 cm and loads were applied at the center of the beam.

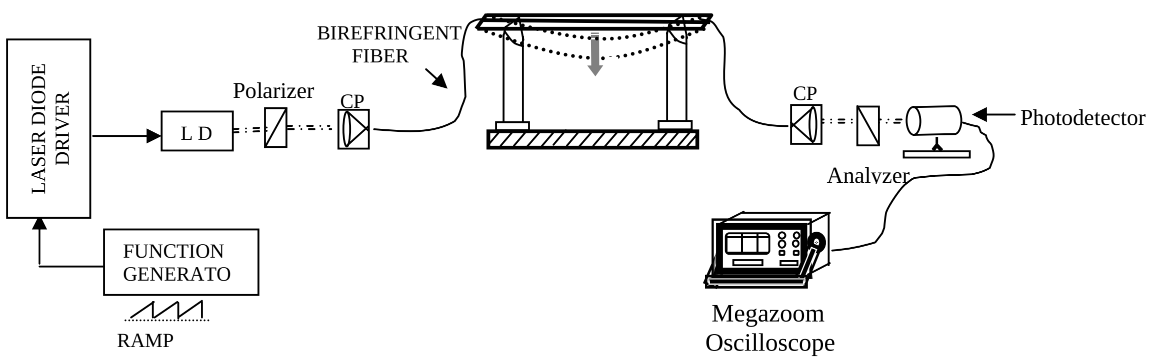

Fig.1. Experimental Set-up: LD-Laser diode, CM-Camera, CP-Optical Coupler, PC- Computer

Optical couplers were used at both ends of the fiber and were coupled to the Laser diode (Melles Griot, 06 DLD 203A, 656.4nm) and a Si-photodetector (Melles Griot) through the polarizer. The Laser diode was operated at 656.4 nm and the output was approximately 10 mw. It was modulated by a saw tooth signal varying from 5Hz to 45Hz with a function generator. To excite LP_{01} mode, the laser beam was focused at the input end of the fiber. With proper launching condition, a Gaussian intensity pattern was observed at the output end of the fiber. At the operating wavelength 656.4nm, the normalized frequency, 'V' of the fiber becomes 3.2. Thus the fiber can support only two lower order modes LP_{01} and LP_{11} as mentioned earlier. To selectively excite the modes, the laser beam was polarized and focused by the microscope objective at the input end of the fiber. The output end of the fiber was imaged by another microscope objective and the near field distribution of the fiber was observed on a near-by screen. The position and angle of the focused laser beam were changed by varying the x-y adjustment of the fiber position. This enabled the observation of lobe patterns of LP_{01} and LP_{11} modes. However, initially the fundamental mode LP_{01} was excited using suitable launching condition. When the load is applied, power exchange takes place between the LP_{01} and LP_{11} modes. The photodetector output was fed to an oscilloscope (Agilent 54621D Megazoom) where digital signal processing was performed using FFT. A specific harmonic of the beat signal provides required information about the measurand at a particular beam position from the detection end. The change in amplitude of the harmonic depends upon the modulating frequency for a given load.

4. RESULTS AND DISCUSSION

The fiber used in our experiment was characterized by cutoff wavelength 800nm (HB-800, Oxford Electronics). So at 656.4nm, by changing launching condition, lower order modes LP01 and LP11 were excited. The detected signal was Fourier transformed using FFT and the different harmonics were displayed. The Hanning window was chosen during FFT operations, as the accuracy of resolving the frequencies is higher compared to other window functions. The interference pattern and their recorded harmonics are shown in fig.2. The birefringent fiber has the following parameters n1 =1.464, n2 =1.456, V=2.6 at 800nm. At the operating wavelength 656.4nm, V-parameter comes out to be 3.2. The beat length of the fiber at 656.4nm comes out to be 0.1832 mm.

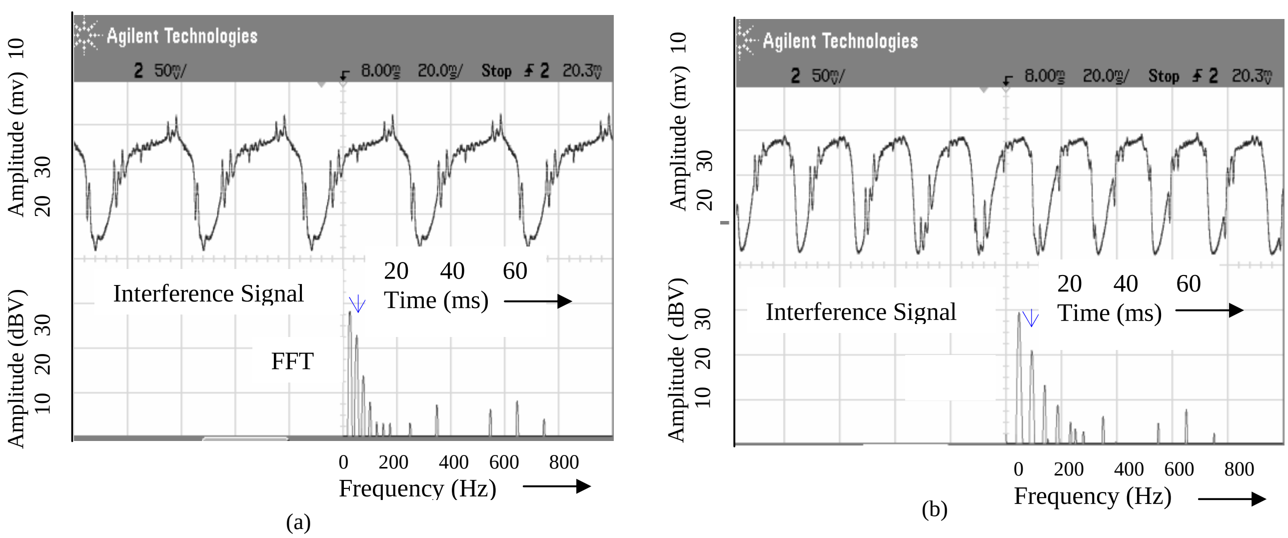

Fig. 2. Interference patterns and FFT recorded at different modulating frequencies: (a) and (b) for 1000 gm at 25 Hz, 45 Hz respectively

The beat frequency was at second harmonic when load was applied at the center of the beam for the modulating frequency of 25 Hz. The magnitude of beat frequency changes with the variation of modulating frequency. According to (5), the distance L (point of disturbance) from the detector end is obtained corresponding to the beat frequency. The amplitude of the beat frequency was measured each time by varying the modulating frequency and it provides the strain distribution at different positions of the beam. The interference patterns captured using CCD camera are shown in fig.3.

(a) 25Hz (b 35Hz (c) 45Hz

Fig.3. Interference patterns recorded in CCD at different modulating frequency (a) 25 Hz (b) 35Hz (c) 45Hz.

The pattern changes at different positions of the beam due to phase variation. The left hand most pattern shown in fig.3(a) represents the fringe pattern obtained when the modulating frequency was 25Hz. It indicates the pattern when the point of disturbance is at the middle point of beam. Likewise the patterns shown in fig.3 (b) & (c) were obtained at 2.0cm and 3.0cm from the central position of the beam by varying the modulating frequency.

Fig.7 shows the strain distribution obtained for the simply supported beam under the loading condition. The results are in good agreement with the theoretical ones.

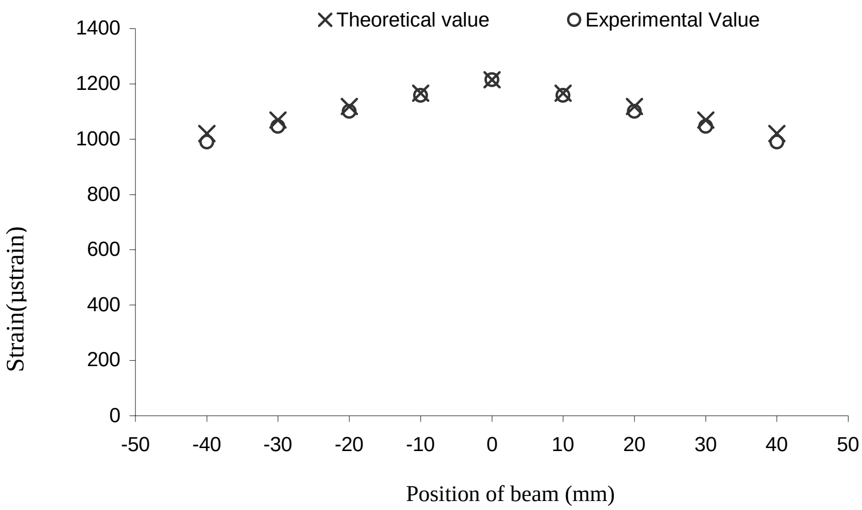

Fig.4. Variation of strain along the beam

The sensitivity of the sensor system depends on the term ($\Delta \beta L$) of the fiber. In our experiment, the birefringent fiber (elliptical core) has the value of $\Delta\beta(= 2\pi n_1 \Delta / \lambda * \partial b)$ = 0.032 rad/µm at 656.4nm. The spatial resolution would depend upon the frequency excursion of the laser source. It was found to be ~ 1.2mm for the present laser source (Melles Griot 06 DLD). The resolution of the sensor system was ~ 20 µstrain (calculated by µstrain/ signal to noise ratio of the corresponding harmonic component).

5. CONCLUSION

We have demonstrated a simple method based on the modal interference in high birefringent fiber for measuring strain distribution in a simply supported beam. The amplitude of the beat frequency at different positions of the beam provides the information about the strain applied to it. Measurement sensitivity would depend upon the mode coupling in the birefringent fiber. It also depends on the type of birefringent fiber. The better sensitivity would be obtained in bow-tie and PANDA fiber due to their appropriate beat lengths at the operating wavelength. The method would be useful in monitoring strain distribution of smart structures and composite materials, particularly in aerospace industry.

Acknowledgement

The authors deeply acknowledge the ISRO (VSSC) for providing the necessary financial support.

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