Strain Measurement in a Mach-Zehnder Fiber Interferometer using Data Dependent System Method

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ABSTRACT
A fiber-optic strain measurement technique based on data dependent system (DDS) in Mach-Zehnderfiber interferometer is presented. The interferogram recorded from the interferometer has been digitized and characterized by means of an autoregressive model. The phase change due to the measurand has been obtained from the self-coherence function of the interferogram. It would provide the phase distribution and modulation of group delay due to measurand. Results are presented for the applied strain in the range of 170-880 µstrain.

General Terms
Fiber optic sensor, fiber interferometer, data processing.

Keywords
Mach-Zehnderfiber interferometer, data- dependent system, strain measurement, interference patterns, phase-extraction.

1. INTRODUCTION
In recent years, fiber optic sensing of different measurands like strain, temperature, pressure, vibration etc. has drawn special attraction because of its compact size, immunity to electromagnetic interference and possibility of real time and long distance measurements. Different types of fiber optic sensors have been reported to get measurand information. Among them, fiber optic interferometric sensors are very attractive because of their high resolution and sensitivity. Out of different fiber optic interferometric techniques, fiber optic Mach–Zehnder interferometers are preferred in sensing applications because of their high sensitivity and simplicity. Flavinet. al. reported a two beam interferometric sensor for measuring strain and temperature simultaneously using dispersive Fourier transform spectroscopy (DFTS) [1]. Recently, P. Lu et.al.has proposed a tapered fiber Mach–Zehnder interferometer fabricated on single-mode fiber by using simple fusion splicing for simultaneous measurement of refractive index and temperature [2]. An asymmetrical fiber Mach–Zehnder interferometer (aFMZI) consisting of a fiber taper and a lateral-shifted junction has been reported for simultaneous measurement of axial strain and temperature [3]. In interferometric sensors, phase change takes place on the application of measurand and the accuracy of measurementdepends upon the extraction of phase from the interferogram. Several methods have been reported for phase extraction from the interferogram. Phase shifting techniques [4], Fourier transform method [5], windowed Fourier transform method [6], parameter estimation method [7], wavelet transform method [8] etc. have been proposed for phase extraction. For higher phase resolution at a high temporal bandwidth, a technique based on sinusoidally modulated phase shifting interferometry has been reported [9]. An all-fiber 3x3 coupler based phase-shifted white-light interferometry has been presented, where the absolute optical path difference (OPD) of Mach–Zehnder interferometer is measured directly [10]. The technique is used to measure static measurands, including strain, temperature and weight and less time is required compared to Fourier transform method. However, experimental difficulty is there for implementation.

In the present work, we propose a phase extraction technique based on data dependent system (DDS) method in a Mach-Zehnder type fiber optic interferometric sensor. The technique does not require global processing to find the phase at a particular point i. e. full length of data set is not used for phase determination. It analyzes discrete data to derive a mathematical model of a real system. The methodology exploits the correlation between the neighboring data points of a profile. A set of data has been selected from the interferogram which is then characterized by means of autoregressive (AR) model. The autoregressive parameters determine the self-coherence function of the interferogram which provides the phase information due to change in measurand. An application has been made for measurement of strain in Mach-Zehnderfiber interferometer.

2. MEASUREMENT PRINCIPLE
In Mach-Zehnder type interferometer, the intensity of theinterferogram generated is given by

$$\mathrm{I} = \mathrm{I}_1 + \mathrm{I}_2 + 2\sqrt{\mathrm{I}_1}\sqrt{\mathrm{I}_2}|\gamma_{12}(\tau)|\cos(\omega\tau - \Psi) \quad (1)$$

where I_1 and I_2 are the intensities of the two arms, $\gamma_{12}$is the normalized coherence function, τ is the time difference of the interfering beams and Ψ is the phase difference between the beams.

The phase imbalance in the sensing arm due to measure and e.g., due to longitudinal strain is given as

$$\Delta\Psi = \Delta\Psi_{\varepsilon} + \Delta\Psi_{\varepsilon T} \quad (2)$$

where the first term represents the imbalance due to strain and the second term due to cross-sensitivity between strain and temperature.

The applied strain on the sensor arm causes the strain optic effect where the strain changes the refractive index of the fiber. Assuming negligible diameter change, the phase imbalance due to strain is [11]

$$\left(\frac{\partial \Psi_\varepsilon}{\partial \varepsilon L}\right) = \left(\frac{2\pi}{\lambda}\right)\left[n - \left(\frac{1}{2}\right) n^3 (2P_{12} + P_{11})\right] \quad (3)$$

where P_{12} and P_{11} are the elements of the strain optic tensor. Thus when a length of one arm of the interferometer is subjected to a measurand, the interference pattern will change. The interferogram has been captured by a CCD camera, and its intensity distribution in one dimension can be expressed as

$$I(x) = 2I_0(x) + \Gamma(x) + \Gamma^*(x) \quad (4)$$

where $\Gamma(x)$ denotes the self-coherence function and $\Gamma^*(x)$ is its conjugate $I_0(x)$ is the background intensity and x is the pixel number. The argument of this coherence function will provide the required phase information due to measurand (i.e. strain, temperature, pressure etc.). When the phase is expanded around a centre optical frequency ω_0 , it may be expressed as,

$$\phi(\omega) = L\left[\beta(\omega_0) + \beta_1(\omega_0)(\omega-\omega_0) + \frac{1}{2}\beta_2(\omega_0)(\omega-\omega_0)^2 + \frac{1}{6}\beta_3(\omega_0)(\omega-\omega_0)^3 + \cdots\right] \quad (5)$$

where $\beta_m = \left|\frac{d^m\beta}{d\omega^m}\right|_{\omega=\omega_0}$, m=0, 1, 2, 3….

represent the imbalances in the propagation constant β and its derivatives. Using DDS method, the phase is recovered from the interferogram and the values of the coefficients of Eq. (5) are determined. They would provide the values of the measurand producing the modulation of group delay.

3. DDS METHOD FOR PHASE EXTRACTION

In DDS method, the intensity pattern obtained from the interferometer may be modulated to get the dependence of a current pixel value I_x at location x in terms of its predecessors $(I_{x-1}, I_{x-2}, ...)$, and the current stimulus a_x by autoregressive model of order n, AR (n) [12]:

$$I_x = \phi_1 I_{x-1} + \phi_2 I_{x-2} + \phi_3 I_{x-3} + \cdots + \phi_x I_{x-n} + a_x \quad (6)$$

where ϕ_i are the autoregressive parameters, and a_x is Gaussian homogeneous noise. The linear least square algorithm has been used to estimate ϕ_i of the AR model.

The AR (n) model can be arranged in a transfer function form and written in terms of the Green's function G_j , where G_j has the form

$$G_j = g_1\lambda_1^j + g_2\lambda_2^j + \cdots + g_n\lambda_n^j \quad (7)$$

where λ_i are the roots of the autoregressive polynomial given by

$$\lambda_n - \phi_1\lambda^{n-1} - \phi_2\lambda^{n-2} - \cdots - \phi_n = 0 \quad (8)$$

and the weighting factor of each λ_i^j is given by

$$g_i = \frac{\lambda_i^{n-1}}{\prod(\lambda_i - \lambda_j)}, \quad 1 \le j \ne i \le n \quad (9)$$

The Green's function characterizes the deterministic components of the process. The convolution of G_j with the residuals a_x produces the real data I_x , obtained during experiment and it provides the self-coherence function as

$$\Gamma_x = \sum_{j=0}^{x} G_j\, a_{x-j} = \sum_{j=0}^{x} g_i\lambda_i^j\, a_{x-j} \quad (10)$$

The phase of the interferogram can be recovered from the argument of the coherence function Γ_x

$$\Phi_x = \tan^{-1}\left(\frac{Im(\Gamma_x)}{Re(\Gamma_x)}\right) \quad (11)$$

This phase is wrapped within the range $-\pi$ to π and it is then unwrapped with suitable algorithm. A program has been developed to calculate the Taylor coefficients of the unwrapped phase and these would provide the required group delay and dispersion due to the measurand.

4. EXPERIMENTAL SETUP

Fig1 shows the experimental setup for Mach-Zehnder fiber interferometer. Light from a He-Ne laser (λ=630 nm) was coupled to the fiber and is split into two components by means of a directional coupler (CP). In the sensor arm, two rods have been used to fix a portion of the fiber (~113mm). One rod has been fixed on an optical bench and another on a translation stage (Newport made, model – 420-s). The fiber has been strained using micro-movement controller. The reference arm has been kept isolated from external perturbations. In sensor arm, measurand field is applied and it changes the dispersion properties of the fiber. The output beams of the two arms have been made collimated by GRIN – rod lenses. The beam combiner (BC) combines the two beams and creates the interference pattern. The intensity patterns have been captured using CCD camera for different strain (170-880μstrain).

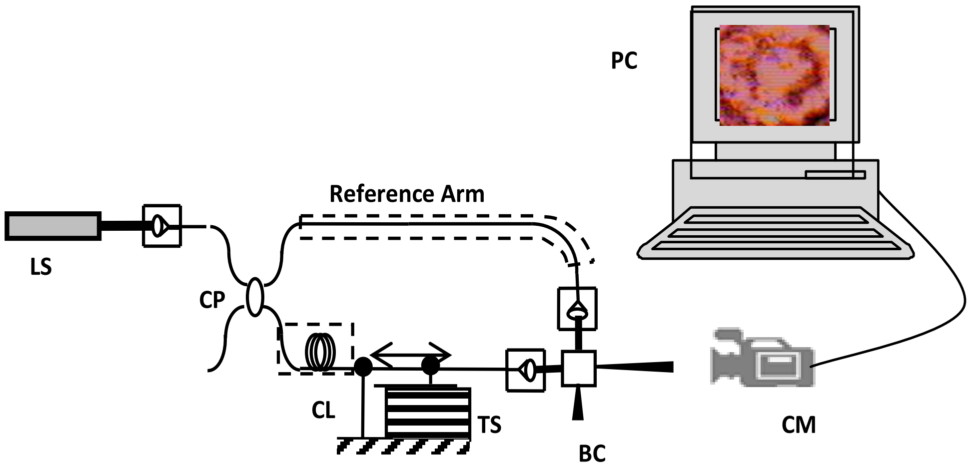
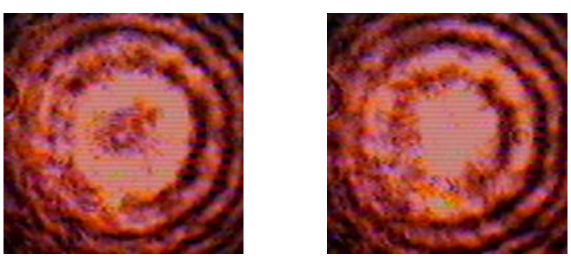


Fig 1: Experimental setup. LS-Laser source, CP-Directional coupler, CL-Clamp,TS-Translational stage, BC-Beam combiner, CM-CCD Camera

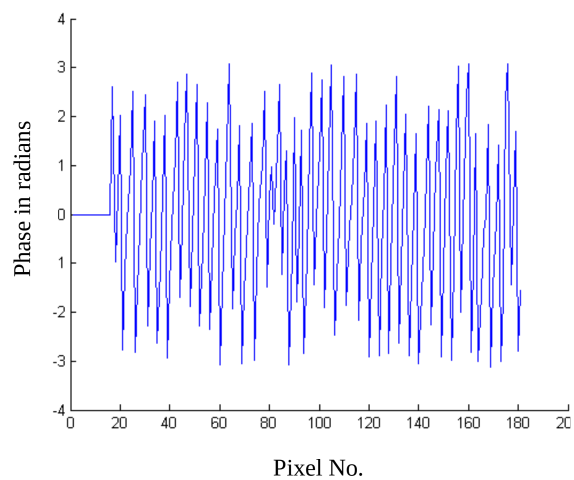
5. RESULTS & DISCUSSION

The interference patterns have been captured using CCD camera for different strain. An image processing algorithm has been developed to digitize the interferogram data and thus to obtain the gray level intensity value for each pixel. The pixel values have been utilized to extract the phase due to measurand change in the interferogram using DDS method.

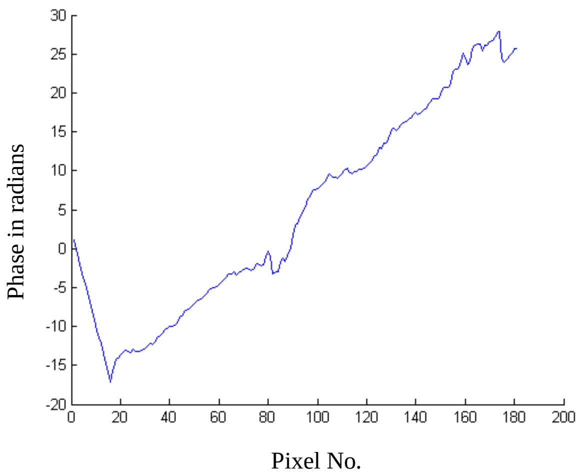


(a) 350 µstrain **(b) 700 µstrain**

Fig 2: Interference patterns for different applied strain

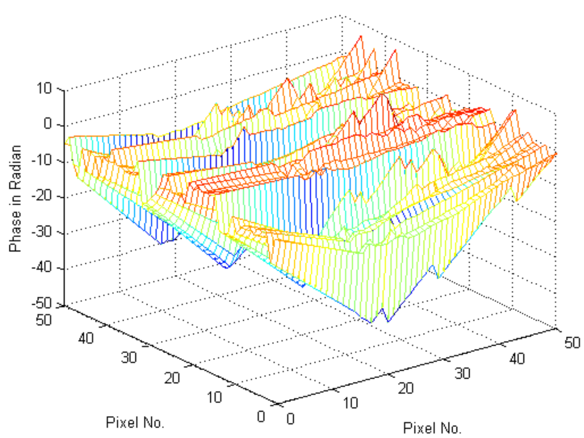


(a) Wrapped phase

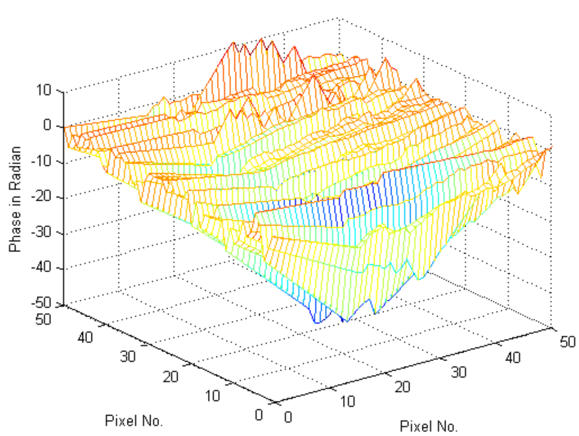


(b) Unwrapped phase

Fig 3: Recovered phase for 700 µstrain



(a) 350 µstrain



(b) 700 µstrain

Fig 4: Phase distribution obtained for different loads

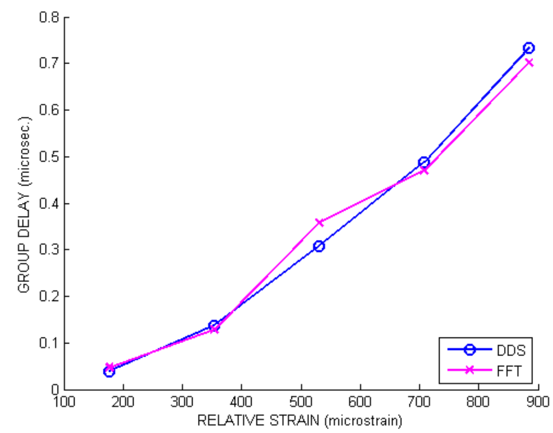


Fig5: Variation of group delay with strain

Fig 2 shows the fringe patterns obtained from the CCD camera using He-Ne laser source for different strains. Using the coding method described in the previous section, the autoregressive model has been selected of the order 15 i.e., AR (15), n=15, then Eq. (6) for one dimensional analysis is

$$I_x = \phi_1 I_{x-1} + \phi_2 I_{x-2} + \phi_3 I_{x-3} + \cdots + \phi_{15} I_{x-15} + a_x \quad (12)$$

for $x = 16, 17, \ldots \ldots, m$

Using fifteen pixel intensities, the roots of the autoregressive polynomial have been determined, and those were used to obtain the self-coherence function of the interferogram which would provide the phase field.Fig 3 shows an example of the wrapped phase and unwrapped phase obtained from the intensity pattern of Fig2(b). We have obtained the phase distribution from the interference patterns under different strain conditions using data dependent system (DDS) method as shown in Fig4.The variations of group delay for different values of relative strain are shown in Fig 5. The results are compared with those obtained with Fourier transform method; better result has been observed with DDS method. The non-linearity of the curve is because of cross-sensitivity which can be minimized with the use of low coherence source.

6. CONCLUSION

We have demonstrated data dependent system (DDS) method for extraction of phase in a Mach-Zehnder type fiber interferometer. It has been implemented for strain measurement in the range of 170-880µstrain. The present technique requires minimum data processing skill and would provide real time processing with proper interfacing. The method provides better result in presence of noise and it is insensitive to errors associated with other techniques e.g. FFT which is used in Fourier transform method. The sensing method would be useful for strain measurement in concrete and composite structures. It can be extended to measure the other physical parameters of structures.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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