ScienceAsia 27 (2001) : **35-40**

Fiber Optic Sensing Applications Based on Optical Propagation Mode Time Delay Measurement

PP Yupapin[a]* and S Piengbangyang[b]

[a] Lightwave Technology Research Center, Department of Applied Physics, Faculty of Science King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand.

[b] National Metrology Institute, Ministry of Science Technology and Environment, Bangkok 10400, Thailand.

* Corresponding author, E-mail: yupapin.preecha@kmitl.ac.th

Received 22 Sep 1999
Accepted 18 Aug 2000

ABSTRACT This paper presents the study of the feasibility of using a linearly polarized, highly coherent source, *ie* HeNe laser with wavelength of 632.8 nm, to produce the optical mode delay time in an optical fiber for the use of sensing applications. Results obtained have shown that the propagation mode delay time measurement in term of optical path difference of 50 μm was achieved respect to the external applied force of 5 N, on the sensing fiber. Other sensing applications such as displacement and bending sensors were also investigated, where the change in optical path difference in term of output detected mode shift of 70 μm was recorded associating with the sensing displacement. The limitation of this measurement due to the sensing fiber bending radius of 2 mm was noted.

KEYWORDS: laser application, optical fiber sensor, fiber optic device.

INTRODUCTION

Optical techniques for measurement were widely used in many areas of applications[1-3], where the different schemes of sensor systems were investigated using laser applications[4-8]. Most of them used low coherent laser sources to produce light beams for the sensor systems, where either optical intensity or phase of the optical field formed the required measurement information. The conventional technique for white light interferometry(WLI) was presented by Ning *et al*,[7] using laser diode. While the use of phase information to form the measurement was investigated and described, using WLI in both theory and experiment by Wang *et al*,[8-10] where the resolution of measurement could be improved by using two alternative sources interferometer. WLI was also demonstrated by Yupapin *et al*[3,6] for the study of photo-elastic material characterizations with the use for sensor applications, where the problem of WLI was light source stability *ie* a laser diode, causing the problem of long period of operation.

The problem of the system employed was easily damage low coherent source due to the power supply voltage fluctuation and circuitry complexity, then the use of highly coherent source was attractive to investigate for sensor applications. HeNe laser was the one known as a highly coherent source which popularly used for intensity measurement technique.

This study was demonstrated that the use of a highly coherent source such as HeNe laser for sensor applications, using phase *ie* optical path difference (OPD) of the traveling light in the optical fibers to form the required information in term of the change of the output light mode position, which could be implemented the required measurement.

OPERATING PRINCIPLES

1. System analysis

The theoretical treatment of physical optics by incorporating the nature of light, where the wave equation in an isotropic media with simple harmonic motion is satisfied the scalar wave equation as

$$\nabla^2 \psi(z,t) = \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\psi(z,t) \qquad (1)$$

where t is time, c is the speed of light, $\psi(z, t)$ is the wave function, and z is distance in the direction of the input traveling wave into the medium refractive index n_1. The phase difference between the input plane (z_o) and output plane (z_1) is the product of the optical path difference and k, which is given as

$$\phi(x) = \frac{2\pi}{\lambda}\left[(n_1 - 1)\,d(x) + \Delta z\right] \qquad (2)$$

where $k=2\pi/\lambda$, d(x) is the traveling distance between planes z_1 and z_o.

Any monochromatic light at wavelength λ that propagates parallel to the z axis which the light wave at plane z_o represented by

$$\psi(z,t) = \sqrt{2} \quad \mathrm{Cos}\,(\omega t - kz_o) \qquad (3)$$

This is spatially modulated by the optical element whose transmitted magnitude is |a(x)| and whose phase is ϕ. From equation (2), where $\Delta z = z_1 - z_o$, light at plane z_1 therefore represented by

$$\psi(z,t) = \sqrt{2}\ \left|a(x)\right|\ \mathrm{Cos}\left[\omega t - kz_o - \phi(x)\right] \quad (4)$$

which shows that light is modulated in the magnitude and phase. To use the phasor notation then the wave equation becomes

$$\psi(z,t) = \left|a(x)\right| e^{j\,[\omega t - kz_o - \phi(x)]} \qquad (5)$$

where the complex transmittance of the optical element is represented as

$$\psi(z,t) = \left|a(x)\right| e^{-j\phi(x) + j\left[\omega t - kz_o - \phi(x)\right]} \qquad (6)$$

The complex transmitted amplitude of several elements in series, as we expect such as

$$a_4(x) = |a_1(x)||a_2(x)||a_3(x)|\,e^{-j[\phi_1(x)+\phi_2(x)+\phi_3(x)]} \quad (7)$$

and the associated real valued represented of the light is

$$a_4(x) = \sqrt{2}\ \left|a_1(x)\right|\left|a_2(x)\right|\left|a_3(x)\right|\ \cos[\omega t - kz_o - \phi_1(x) - \phi_2(x) - \phi_3(x)] \qquad (8)$$

Any physical detector senses the intensity of light, defined as

$$I(x,y,z) = a(x,y,z,t)\,a^*(x,y,z,t) \qquad (9)$$

For the real valued version of the equation (8) and find that the intensity at plane z_1 becomes

$$I = 2\ \left|a(x)\right|^2 \left\{\frac{1}{2} + \frac{1}{2}\mathrm{Cos}\,[2\omega t - 2\,kz_o - 2\phi(x)]\right\} \quad (10)$$

A photo-detector responds to the time average of I(x, t) to produce the current g(x) that is a function of only the space variable

$$g(x) = \langle I(x,t) \rangle = \left|a(x)\right|^2 \qquad (11)$$

The system in the study is concerned the photo-current or the optical field intensity which is in the form as in equation(10).

2. Propagation modes

The optical field(E) from a linearly polarized light in xy-plane of a highly coherent source is expressed in term of the Gaussian light output beam as

$$E(x,y) = E_o \exp\left(-\frac{x^2+y^2}{\omega^2}\right) \qquad (12)$$

where x and y are the laser beam coordinates, E_o is the optical field amplitude, ω_o is the initial beam width, i.e. z = 0, a laser beam width (ω) is given as

$$\omega(z) = \omega_o\left[1 + \left(\frac{2z}{r}\right)^2\right]^{1/2} \qquad (13)$$

where r is a spherical mirror radius. Consider light modes propagation in a fiber which is described by a normalized wave number (V) as

$$V = \frac{2\pi}{\lambda} a\,NA \qquad (14)$$

where λ is a light source wavelength, a is a fiber optic core radius, and NA is a fiber optic numerical aperture. The number of propagation modes(N) is given by

$$N \cong \frac{V^2}{2} \qquad (15a)$$

for single mode fiber, and

$$N \cong \frac{V^2}{4} \qquad (15b)$$

for multimode fiber.

Consider the optical field intensity (I) of the transmitted light through the optical bulky grating which is detected by a photo-detector, the grating transfer function of the optical output is expressed as

$$I(x) = \frac{a^2}{2}\{1 + \mathrm{Cos}\,\varphi(x)\} \qquad (16)$$

where $\varphi(x) = (\phi_1-\phi_2)$ is the phase difference of two propagation modes, a is a signal amplitude. The optical output intensity is associated with equation (16), the phase difference $[\varphi(x)]$ is observed in term of OPD by moving the detector position to obtain the optimum detected intensity position, then the measurement relationship of the change between phase and optical path difference is observed. The mode separation of the transmitted light modes through the bulky grating is given as the equation

$$m\lambda = a(\sin\theta_i + \sin\theta_m) \quad (17)$$

where a is a grating period, θ_i and θ_m is the incident and diffraction angles respectively, m is the light diffraction order, λ is the light source wavelength. Any change of light mode traveling path is effect to the output light mode separation, i.e. OPD which is observed and detected by a photo-detector respect to the change on the sensing fiber which will be discussed in the following sections.

3. Sensing Applications

There are other factors of fiber bending to take into account in addition for sensor considerations, which can be divided into two general cases as following. The fiber micro-bending sensitivity, is represented by $\Delta L/\Delta D$, where the mechanical design of the bending sensing device, associated with $[\Delta D/\Delta F]$[11] is expressed as

$$\frac{\Delta L}{\Delta F} = \frac{\Delta L}{\Delta D}\frac{\Delta D}{\Delta F} \quad (18)$$

where L is the fiber transmission length, F is the applied force, and D is the deformation length of the fiber normal to its axis.

Sensitivity to micro-bending, or large $\Delta L/\Delta D$, is increased by small values of numerical aperture, a large number of deformations, optimized perturbation period, and a large core diameter relative to cladding diameter. Mechanical design considerations may against some of those selections, since to maximize $\Delta D/\Delta F$, a small diameter fiber, few bends, and a large perturbation wavelength are desire. One example of the many influences on the total sensitivity of the micro-bending sensor is given by the length dependence of micro-bending sensitivity, it is written as

$$\frac{\Delta L}{\Delta D} \alpha \quad l^q \quad (19)$$

where l is the length of the micro-bent fiber, and $0<q\leq 1$. A fiber with a perfectly absorbent jacket would have q = 1 and a sensitivity that depended linearly on the sensing length.

The another application is the fiber optic strain sensor, (*ie* strain = applied force/ fiber length), then equation (18) can be used similarly to micro-bending sensor. In this scheme, the transmission term ΔL is relatively changed to the applied force with respect to the fiber coupling length an shown in Fig 1.

Both schemes, the transmission light is detected by a detector after passing through the transmission grating. The detector output light modes are observed relating to the applied physical parameters. Strain and bending measurements are observed by using the applied force on the sensing unit which the effects are transformed into the fiber bending section, *ie* the optical path difference of the propagation modes. In application, a system may be employed by using the another single mode fiber known as polarization maintaining fiber(HiBi fiber), having highly birefringent fiber as a sensing fiber. The broader applications such as temperature sensor and the difference fiber optic characteristics can be investigated.

A change in temperature ΔT of a fiber changes the fiber length due to thermal expansion or contraction, and change the refractive index. Thus, if the phase of the transmitted light $\varphi = (2\pi l n)/\lambda$, the following may be written as[12]

$$\left(\frac{\Delta\phi}{\Delta T}\right) = \left(\frac{2\pi}{\lambda}\right)\left[n\left(\frac{dl}{dT}\right) + l\left(\frac{dn}{dT}\right)\right] \quad (20)$$

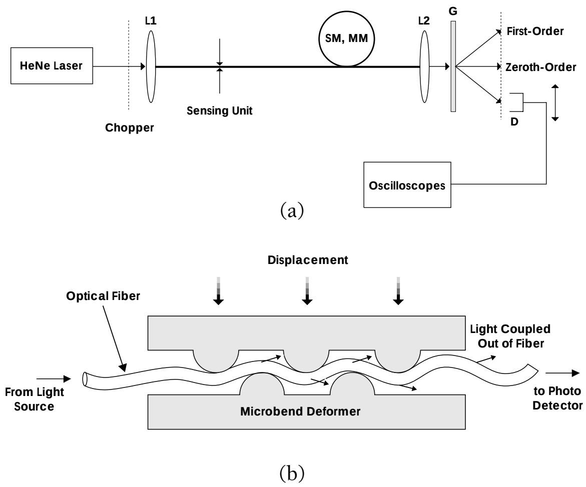

Fig 1. The illustration of the experimental system (a), and a sensing unit (b). L1, L2: Lenses, SM: Single mode fiber, MM: Multimode fiber, G: Grating, and D:Photdetector.

for an ordinary single mode fiber, and

$$d\left(\frac{\Delta\phi}{\Delta T}\right)=\left(\frac{2\pi}{\lambda}\right)\left[\left(\Delta n\frac{dl}{dT}\right)+l\left(d\left(\frac{\Delta n}{dT}\right)\right)\right] \quad (21)$$

for a HiBi fiber, where l is the fiber length, n is the refractive index of the sensing fiber, and λ is the light source wavelength. The change of the optical phase due to mode propagation time delay will change the output intensity as described by equation(16).

The difference between equations (20) and (21) is that the ordinary mode fiber is supposed to be completely symmetry then the fiber birefringence is vanished, the latter case of equation (21) is the special fiber called polarization maintaining fiber which the fiber birefringence is presented, for temperature sensor applications. The change of temperature affects to the change of fiber length and birefrngence. The relationship between temperature and phase or light intensity is the detected parameter using a photo-detector, where the detected intensity is specified by output wavelength variation as in equation (17).

Experiments and Results

Light from He Ne laser with wavelength of 632.8 nm was linearly polarized then launched into a length of single mode/multimode fiber, with 6 meters long as shown in Fig. 1, before entering into a sensing fiber and bulky optical grating. The bulky grating with 1200 lines in 1 milliimeter was aligned with 10 cm apart from a detector. In order to avoid the background noise from the direct current, then a mechanical chopper was employed to chop the light beam being the ac signal i.e increasing the signal to noise ratio of the detected signals. A single Gaussian mode from HeNe laser was chopped then launched and split into several modes by traveling through the length of delivery fiber and sensing unit, before entering into a bulky grating. The output light was detected by a detector and shown on the oscilloscope.

The change of light path due to the external applied physical parameters such as the external applied forces were formed and identified position by moving the detector position to obtain the maximum signal amplitude and OPD. This may be related to the change of the required information such as force and displacement. In this work, the applied force was applied on the sensing unit by using the series of calibrated masses. The measurements were made of 5 times for each data point. The increment of scanning resolution and applied of 10 microns and 0.2 N were used for displacement and force measurement respectively.

Fig 2 shows the change of the detector position (optical path difference) from light traveling trough the sensing unit which was formed and detected using single mode fiber and multimode fibers respectively, where the measured values of mode

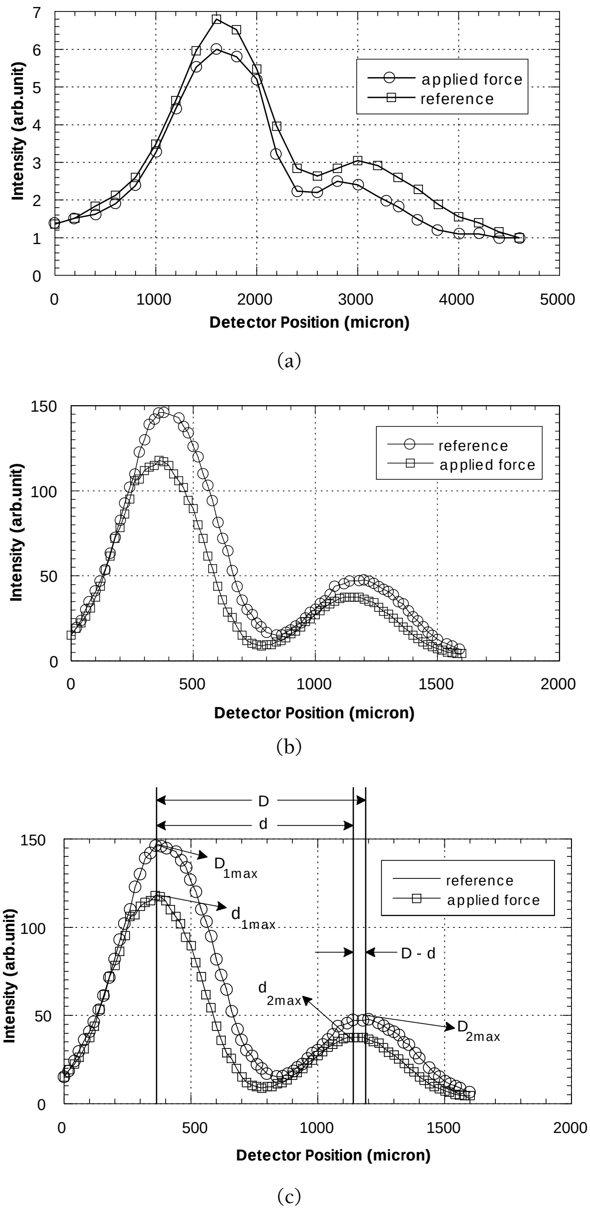

Fig 2. Shows graphs of the detected output mode position intensities either with or without force (reference), using, (a) single mode fiber, (b) multimode fiber, and (c) the measurement (D-d) of the change of the detector position using multimode fiber. Where D and d is the distance of the center peak of the reference signal. D_{max} and d_{max} is the center peak signal with respect to the applied force.

separation of 50 µm was achieved. Generally, propagation modes separation is obtained from mode propagation time delay along a fiber forming the reference position *ie* 1st order mode position. The change of physical parameters along the sensing fiber was induced the change of first order mode and detected by the detection device, then was measured. In this study, the change in propagation modes of traveling light in the fiber means the change in spectral width *ie* wavelength, which is observed.

Fig 3 shows the result of the change of mode position / wavelength difference which was induced by the applied force, where the change of the detector position/OPD of 50 µm was noted associating with the applied force of 5 N, SM: single mode fiber, MM: multimode fiber. The presented data was used the statistical method then plotted with systematical error bar of 10 micron. The change of first order mode of 70 and 90 µm was observed respecting to the sensing displacement of 0.5 mm, for multimode and single mode fiber respectively. The increasing of propagation modes was effected the output detection measurement which may be obtained from the intensity noise of the neighboring harmonics *ie*

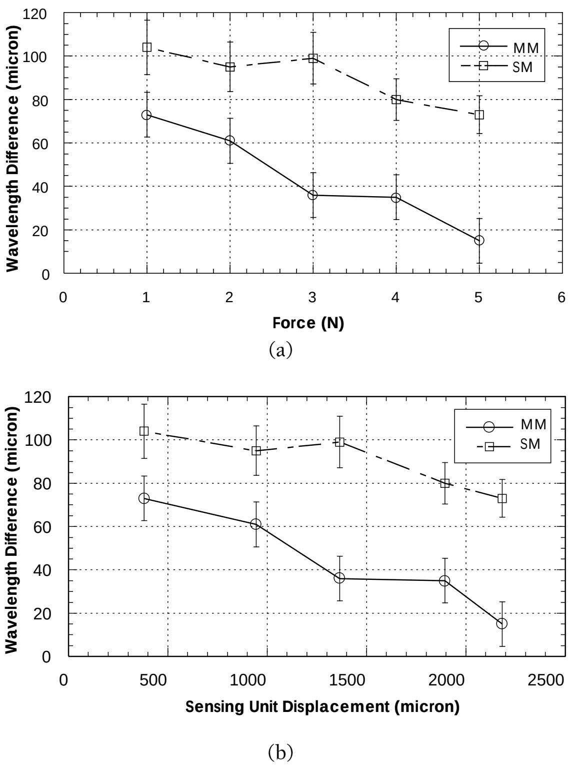

Fig 3. Graphs of the relationship between the change of mode detection position with respect to the applied force (a) and sensing unit displacement (b). SM: Single mode fiber, MM:Multimode fiber.

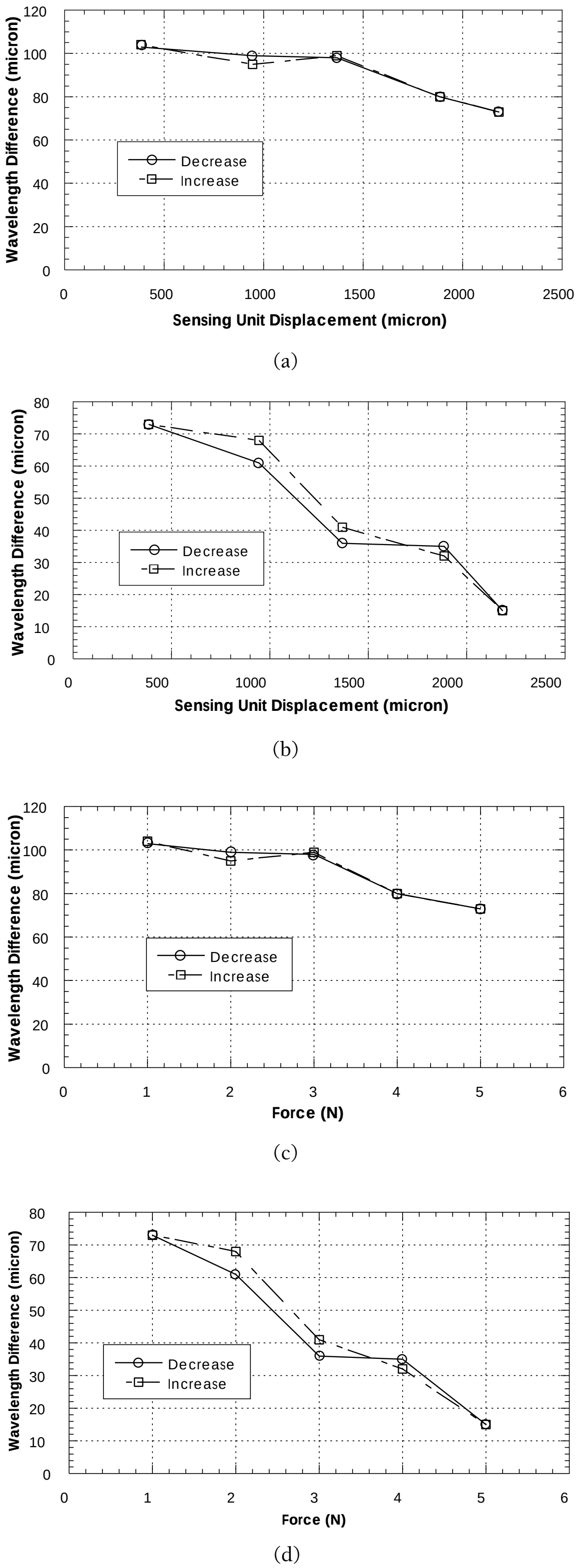

Fig 4. Graphs of the measurement hysteresis for the force sensing experimental system using single mode (a) and multimode fiber (b), the displacement experimental scheme using single mode (c), and multimode fiber(d).

modes. Fig 4 shows the result of the measurement hysteresis of the systems for force and displacement measurements, using either single or multimode mode fibers having small hysteresis for both systems.

Conclusion

The study of the use of a highly coherent source for sensing application was presented. The subject of this study was concentrated on the simple measurement technique which widely used for sensor and optical metrology applications. Results have shown the potential of using a technique of light mode separation measurement in such a fiber for force, fiber bending, and displacement sensors. The detected resolution of the output mode separations was founded in the range of 10 microns. To improve the resolution, the scanning device such as a nano-scanning device using piezoelectric transducer(PZT) system may be employed. However, the signal detection levels may limit the measurement due to the invalid values of SNR. The comparison of the systems use ordinary single mode fiber and multimode fiber was proposed, the single mode fiber has shown more advantage than the one using multimode fiber.

Acknowledgements

The authors are pleased to acknowledge some support from the National Electronic and Computer Technology Center (NECTEC) by way of a research scholarship to Assoc Prof Dr Preecha Yupapin.

References

1. Weir K *et al* (1994) Accurate measurement of small displacement using optical techniques. *Int J Optoelectronics* 9, 449-55.
2. Yupapin *et al* (1998) Dynamic measurement of thin liquid film parameters using high-speed ellipsometry. *Sensors Actuators A* 65, 19-22.
3. Wang A *et al* (1992) Optical fiber pressure sensor based on photoelasticity and its applications. *J Lightwave Technol* 10, 1466-72.
4. Yupapin PP and Kusamran S (1993) Photoelastic material characteristics based on the stress-induced effects for sensor applications, *Smart Mater Struct* Vol 2, 1993, 157-61.
5. Yupapin PP *et al* (1996) Fiber optic force sensor and its applications. *Thammasart Int J of Sci and Technol* 1, 5-10.
6. Yupapin PVP *et al* (1993) An optical pressure sensor using a low - coherence light source with a photoelastic sensing element. *Sensors and Actuators A* 36, 105-11.
7. Ning YN *et al* (1989) Characteristics of laser Diodes for interferometric use. *Appl Opt* 28, 3657-81.
8. Yupapin PVP *et al* (1995) A study of polarization maintaining fiber characteristics with applications to force and displacement sensing. *J Laser Applications* 7, 89-97.
9. Wang DN *et al* (1993 The optimized wavelength combinations of two broadband sources for white light interferometry. *J Lightwave Technol* 11, 909-16.
10. Wang DN *et al* (1994) Alternative white light interferometer. *J Lightwave Technol* 12, 961-66.
11. Udd E (1995) Fiber optics smart structures, John Wiley & Sons Inc, New York.
12. Udd E (1991) Fiber optics sensors:An Introduction for Engineers and Scientists, Toronto: John Wiley & Sons.