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A Fiber Optic Interferometric Sensor for Dynamic Measurement

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Abstract**—**An optical fiber Fabry-Perot interferometer (FFPI) is proposed and demonstrated for dynamic measurements in a mechanical vibrating target. A polishing metal with a low reflectance value adhered to a mechanical vibrator was excited via a function generator at various excitation frequencies. Output interference fringes were generated by modulating the reference and sensing signal at the output arm. A fringe-counting technique was used for interpreting the displacement information on the dedicated computer. The fiber interferometer has been found the capability of the displacement measurements of 1.28 μm – 96.01 μm. A commercial displacement sensor was employed as a reference sensor for investigating the measurement errors from the fiber sensor. A maximum percentage measurement error of approximately 1.59 % was obtained.

Keywords**—**Optical fiber sensors, dynamic displacement, fringe counting, reference displacement sensor.

I. INTRODUCTION

THE field of fiber optics has undergone tremendous growth and advancement over the last 25 years. Initially conceived as a medium to carry light and images for medical endoscopic applications, optical fibers were later proposed in the mid 1960's as an adequate information carrying medium for telecommunication applications. Ever since, optical fiber technology has been the subject of considerable research and development to the point that today lightwave communication systems have become the preferred method to transmit vast amounts of data and information from one point to another. Among the reasons why optical fibers are so attractive are their low loss, high bandwidth, safety, relatively low cost, low maintenance, etc [1].

In the early 1970s, the first experiments were conducted on the low-loss optical fiber being used, not for telecommunications, but for sensor purposes. Such devices are called optical fiber sensors (OFSs). They have several advantages over conventional sensing technologies such as small size, light weight, high sensitivity, high temperature capabilities, immunity to electromagnetic interference, and potential for large-scale multiplexing. The increased use of optical fiber components in telecommunications networks has resulted in mass production of several electrical and optical components which are used in optical fiber sensor systems as well. This increased component availability has contributed to reduce optical sensor system costs [2]. They are also attractive for applications in sensing, control and instrumentation. In these areas, optical fibers have made a significant impact. For these applications fibers are made more susceptible and sensitive to the same external mechanisms against which fibers were made to be immune for their effective operation in telecommunications. Other advantages such as proven non-destructive testing capability, radio-frequency interferences, accessibility to difficult areas, and criteria which cannot be achieved with traditional sensing technology are properties which have been exploited [3]. Conventionally, the main physical properties measured are the intensity, phase, wavelength and state of polarization of the guided light [4].

Fiber optic interferometry (FOI) is a sub-type of OFSs that can thus be classified into two categories: two-beam and multiple-beam interferometers. Two-beam interferometers can be exploited in the Michelson, Sagnac, and Mach-Zehnder configurations. The interference signals are obtained from modulating two cosinusoidal signals between reference signal, reflected light from an isolated fiber arm serving, and sensing signal, back-reflected light from the target movement. Many applications use these sensors e.g. for ultrasonic location, harsh aerospace environments, and acoustic measurements [5], [6].

Fiber-based Fabry-Perot interferometer (FFPI) is a typical multiple-beam interferometer. It consists of a single-mode fiber with cleaved end faces and a sensing element, surface. The space separating of the reflecting surface is called the cavity length. The reflected light in the FFPI is wavelength-modulated in exact accordance with the cavity length. It can be used in various sensitive applications such as measuring velocity, displacement, strain, temperature and stiffness measurements [7], [8].

In this work, we used an optical fiber-based Fabry-Perot interferometer for dynamic displacement measurements. A vibrating target was excited by a mechanical vibrator via a function generator in various excitation frequencies. An interference signal was generated from the modulation between the two sets of reference and sensing signals at the output arm of the fiber interferometer detected by a detector. A fringe-counting technique was used for counting the

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number of interference fringes. This number was then converted to displacement information. One fringe period is equivalent to a displacement of a half of the wavelength (λ/2). A commercial displacement sensor was employed as a reference displacement sensor for comparison with the measured information from the fiber interferometer. A program written in Visual C++ was developed for counting the number of fringes and plotting the displacement information with a resolution of λ/2 on a dedicated computer.

II. PRINCIPLE OF OPERATION

In general, the classical configuration of the fiber-based Fabry-Perot interferometer for dynamic displacement measurement is illustrated in Fig. 1.

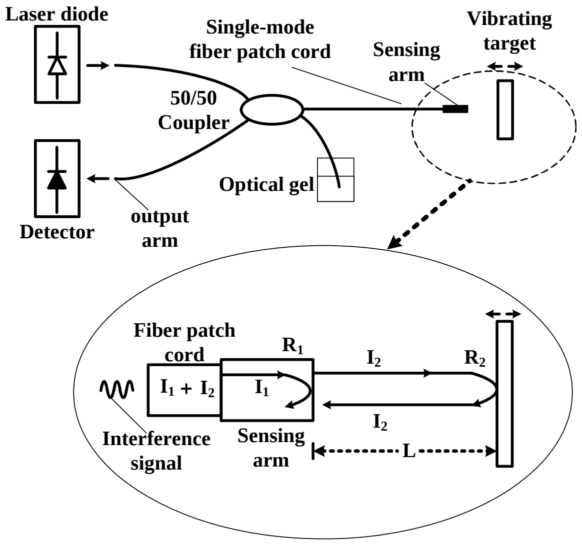

Fig. 1 Principles of an optical fiber-based Fabry-Perot interferometeric sensor

The optical FFPI can be approximated as a two-beam interferometer due to the inherent property of the fiber interferometer. When the laser diode light arrives at the fiber end-face, a portion is reflected off the fiber/air interface (R_1) and the remaining light propagates through the air gap (L) with a second reflection occurring at the air/fiber interface (R_2). In an interferometric sense, R_1 is the reference reflection called the reference signal (I_1) and R_2 is the sensing reflection or sensing signal (I_2). These reflective signals interfere constructively or destructively based on the optical path length difference between the reference and sensing signals which is called the interference signal [9]. Therefore, small movements of the vibrating target cause a change in the gap length, which changes the phase difference between the sensing and reference signals producing fringes. The expression for calculating the output intensity *(I)* is given by [10]

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\Delta\phi \qquad (1)$$

where I_1 and I_2 are the reference and sensing intensities for the back reflection beams from reference and sensing signals, respectively. $\Delta\phi$ represents the total phase difference between both components. Since the phase is directly related to the variation of the cavity length, any changes to the optical path length will result in a change to the phase-shift term given by

$$\Delta\phi = \frac{4\pi n \Delta L}{\lambda} \qquad (2)$$

where *n* is the refractive index of the cavity, λ is the laser diode center wavelength and ΔL is twice the cavity length variation. Therefore, the output displacement information of the mechanical vibrating target can then be obtained from the changes in the cavity length which related to the variation of the phase difference from both signals. However, an expression for investigating the displacement *(D)* is given by (3) which the number of fringes *(N)* in a period time being corresponds to the displacement value [11].

$$D = N\frac{\lambda}{2} \qquad (3)$$

III. EXPERIMENT AND RESULTS

The experimental set-up of the fiber-based Fabry-Perot interferometer for dynamic displacement measurements is designed and illustrated in Fig. 2.

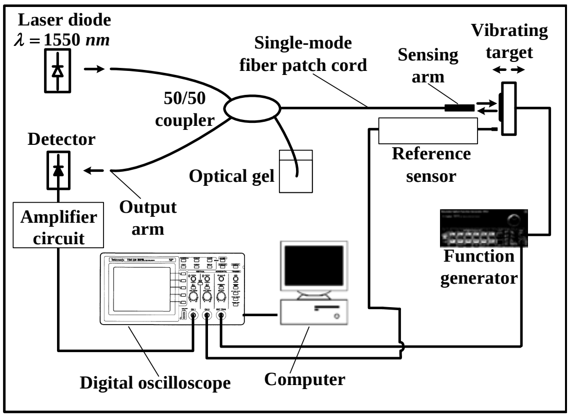

Fig. 2 Experimental set-up of fiber-based Fabry-Perot interferometer for dynamic displacement measurement

Lightwave from a single-mode fiber-pigtailed distributed feedback laser *(LASERMATE)* with a wavelength of 1550 nm, integrating an optical isolator for eliminating back-reflections into the laser source, is injected into the input arm of a 50/50 fiber coupler and then propagated to the sensing arm of the interferometric device. Approximately four percent of the injected laser light is reflected back into this fiber arm at the fiber-air interface as the reference signal while the remaining light is next transmitted into the surface target and then reflects off the polishing metal target which is secured to a mechanical vibrator and excited via a function generator in range of ~2 Hz – 1.5 kHz. This beam re-injected back into the fiber arm along the optical path is called the sensing signal while another arm of the fiber coupler (see Fig. 2) is not used and is put into the optical gel for reducing or eliminating reflection losses. Two interfering beams (reference and sensing) from the sensing arm are then guided along the output arm of the fiber coupler and are next detected by a detector. The interference signal is thus generated and then displayed on a digital oscilloscope. Fringe processing can then be carried out using a dedicated computer to obtain the displacement information via a developed program written in Visual C++ language. A commercial displacement sensor *(Keyence model EX305V)* with a sensitivity of ~0.4 µm is employed as the reference sensor for comparison with data obtained from the fiber interferometer. A set of the interference signal measured by the fiber interferometer and the reference displacement curve from the reference sensor are displayed in Fig. 3.

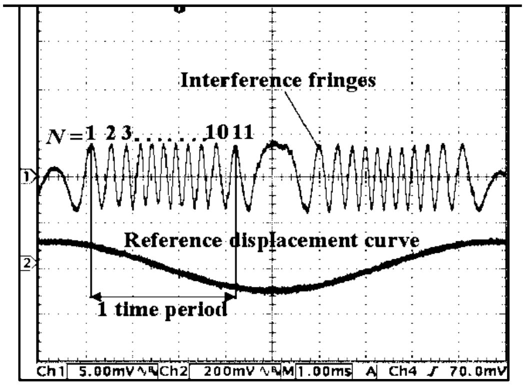

Fig. 3 Output interference fringes measured by FFPI sensor and displacement curve from reference displacement sensor

The figure showed the experimental results from the excitation frequency and amplitude of ~900 Hz and 5 V, respectively. The output interference signal exploited the number of fringes of 11 signals in a time period, leading to a displacement of ~8.6 µm was achieved while the output displacement measured by reference sensor was 8.69 µm. In addition, the summary of the output displacement information obtained from the excitation frequency in various ranges from 2 Hz to 1.5 kHz are then plotted in Fig. 4.

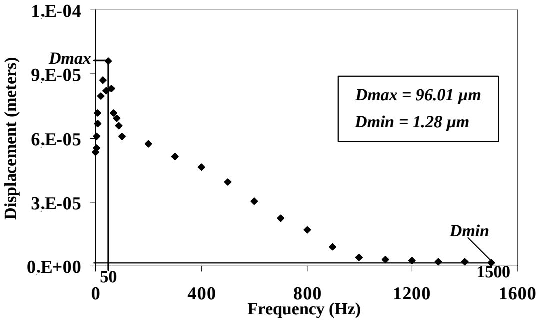

Fig. 4 Relationship between variation frequencies and displacement information measured by FFPI sensor

The experimental results found the capability of the fiber interferometer for dynamic displacement measurements in various excitation frequencies with a minimum and maximum displacement of ~1.28 µm and ~96.01 µm, respectively were achieved, while the reference sensor obtained minimum and maximum displacements of 1.25 µm and 96.39 µm, respectively. By comparison the output displacements information between the fiber interferometer and reference sensor, a maximum percentage dynamic displacement measurement error of 1.59 % was obtained. The relationship of the output dynamic displacements measured by the two sensors is plotted in Fig. 5.

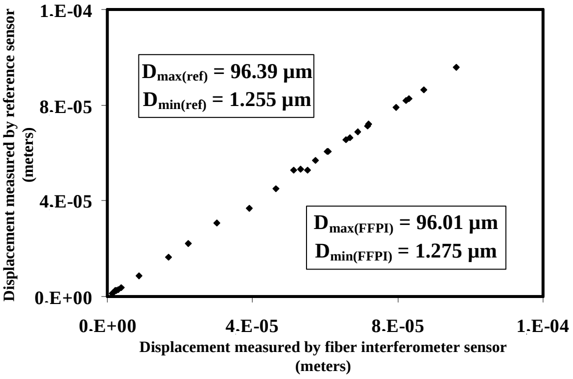

Fig. 5 Relationship between output displacement information measured by FFPI sensor and reference displacement sensor

The developed program was employed for fringes counting processing and plotting of the displacement information which was associated with the output interference signal. At each step the output displacement information is related to the number of fringes which were generated using the fringes counting technique. This technique counts each peak or maximum intensity of the output interference fringes as a one number of fringes. Therefore, the relationship between the output interference signal measured by the FFPI sensor and the displacement curve which was plotted by the developed program with the resolution of $\lambda/2$ (or ~755 nm at λ_{laser} = 1550 nm) can be obtained. It is illustrated in Fig. 6.

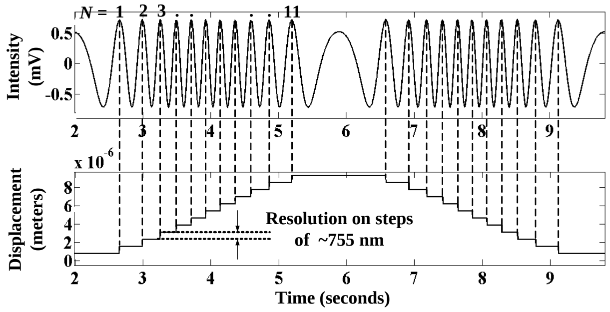

Fig. 6 Output interference signal and displacement curve plotted by developed program written in Visual C++

IV. CONCLUSION

In this paper, we demonstrated an optical FFPI sensor for dynamic measurement. A mechanical vibrator adhered to the polishing metal with low reflectance value has been employed as the mechanical vibrating target. The variable excitation frequencies from ~2 Hz to 1.5 kHz have been used to excite the target. The output displacements can exploit the potential of the fiber interferometric sensor to detect the desired measurement reliably. A Visual C++ - based program was developed for plotting the relative displacement curve from the output interference fringes with the resolution of ~755 nm /steps. Last but not least, the output dynamic displacement measurements from approximately 1.28 μm up to a maximum displacement of 96.01 μm have been achieved by the interferometer. A maximum percentage measurement error of approximately 1.59 % was obtained by comparison with a commercial displacement sensor.

REFERENCES

[1] E. UDD, Ed., *Fiber Optic Sensor: An Introduction for Engineers and Scientists*, New York, Wiley & Sons Inc., 1991.

[2] B. Culshaw and J. Dakin, “Optical Fiber Sensors: Systems and Applications”, *Artech House*, vol. 2, Norwood, 1989.

[3] F. T. S. Yu and S. Yin, *Fiber Optic sensor*, New York, Marcel Dekker Inc., 2002.

[4] D. A. Krohn, “Fiber Optic Sensors: Fundamental and Applications”, *Instrument Society of America, Research Triangle Park*, North Carolina, 1988.

[5] P. Fomitchov, T. W. Murray, and S. Krishnaswamy, “Intrinsic fiber-optic ultrasonic sensor array using multiplexed two-wave mixing interferometry”, *Appl. Opt*., vol. 47 no. 2, pp. 1262-1266, 2002.

[6] A. Dandridge, *Fiber Optic Sensors Based on the Mach-Zehnder and Michelson Interferometers in Fiber Optic Sensors: An Introduction for Engineers and Scientists*, New York, Wiley & Sons Inc., 1991.

[7] N. Singh , S. C. Jain, A. K. Aggarwal and R. P. Bajpai, “Develop and experiment studies of fibre optic extrinsic Fabry-Pérot interferometric sensor for measurement of strain in structures”, *Current Science*, vol. 86, no. 2, pp. 309-314, 2004.

[8] T. K. Gangopadhyay and P. J. Henderson, “Vibration: history and measurement with an Fabry-Pérot sensor with solid-state laser interferometry”, *Appl. Opt*., vol. 38, no. 12, pp. 2471-2477, 1999.

[9] M. Born and E. Wolf, *Principle of Optics*, London, Cambridge University Press, 2002.

[10] P. C. Beard and T. N. Mills, “Extrinsic optical-fiber ultrasound sensor using a thin polymer film as a low-finesse Fabry-Perot interferometer”, *Appl. Opt*., vol. 35, no. 4, pp. 663-675, 1996.

[11] T. K. Gangopadhyay, S. Chakravorti, K. Bhattacharya and S. Chatterjee, “Wavelet analysis of optical signal extracted from a non-contact fibre-optic vibration sensor using an extrinsic Fabry-Perot interferometer”, *Meas. Sci. Technol*., vol. 16, pp. 1075-1082, 2005.