Journal of the Optical Society of Korea, Vol. 4, No. 2, September 2000, pp. 89-93

Absolute Temperature Measurement using White Light Interferometry

Jeong Gon Kim

Department of Information and Communication Engineering, Hansei University, Kunpo 435-742, KOREA

(Received May 09, 2000)

Recently a new signal processing algorithm for white light interferometry was presented. In this paper, the proposed signal processing algorithm was applied for absolute temperature measurement using white light interferometry. Stability testing and absolute temperature measurement were demonstrated. Stability test demonstrated the feasibility of absolute temperature measurement with an accuracy of 0.015 fringe. The test also showed that the absolute temperature measurement system using white light interferometry is capable of obtaining the theoretical minimum detectable change (0.0005 fringe), which is consistent with the performance predicted by the proposed signal processing algorithm.

I. INTRODUCTION

In order to fully utilize the capability of fiber optic sensors, a fiber optic sensor with a new sensing principle termed "White Light Interferometry" (WLI) was developed [1]. White light interferometry differs from conventional interferometry in that it uses a broadband light source. Two interferometers, the sensing interferometer and the processing (scanning) interferometer, are connected in tandem. For white light interferometry, the zero order fringe peak is the peak with the highest fringe visibility amplitude and the absolute Optical Path Difference (OPD) of the sensing interferometer is known if the zero order fringe peak is identified. White light interferometry has the potential to identify the interference fringe order from the output pattern of an interferometer [2]. But, for most broadband light sources, the visibility of fringes varies so slowly in the vicinity of the zero order fringe peak that a high signal-to-noise ratio is required to identify the zero order fringe simply through inspection of its magnitude. This difficulty has inhibited the application of fiber optic sensors using WLI for absolute OPD determination [3]. Recently, the author presented a new signal processing algorithm for white light interferometry, and the proposed signal processing algorithm has been proven to be effective for absolute temperature measurement [4]. Computer simulation of the proposed signal processing algorithm identified the zero order fringe peak with a miss rate of 0.0003 at 31 dB signal-to-shot noise ratio. Also, at 35 dB signal-to-shot noise ratio, resolution of 10^{-3} fringe was obtained. This paper describes the demonstration of such a signal processing algorithm and compares the absolute temperature measurement with a performance prediction based on published data from a previous report.

II. ALL FIBER WHITE LIGHT INTERFEROMETRY

In this section All Fiber White Light Interferometry (AFWLI) is briefly introduced. Over the past two years the fiber optic lab at in Texas A & M university has been developing it using the configuration of Fig.1. From the beginning of this research, the objective has been to develop the signal processing algorithm for an AFWLI temperature measurement system. First, the principle of absolute temperature measurement for this AFWLI is explained. It consists of three interferometers: the sensing interferometer, the reference interferometer, and the processing interferometer. Fiber Fabry-Perot interferometers (FFPI) were used as a sensing interferometer and also a reference interferometer. An All Fiber Mach-Zehnder Interferometer (AFMZI) was used as a processing interferometer and approximately 30 m of single mode fiber was wrapped around in two layers on Piezoelectric Transducers (PZTs) inserted in the scanning arms

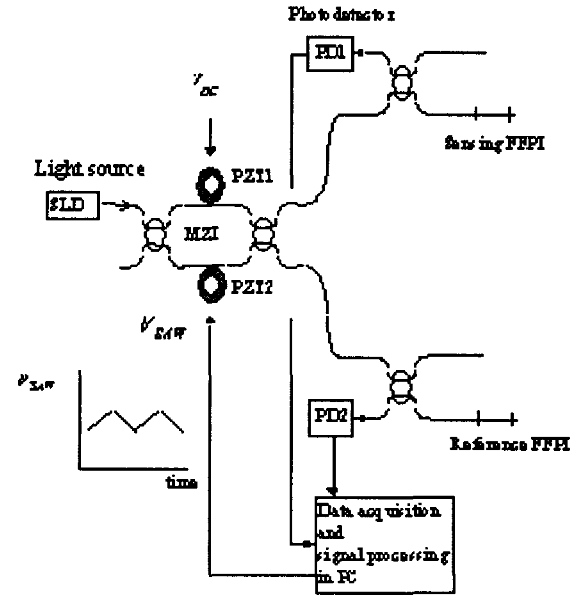

FIG. 1. All Fiber White Light Interferometer

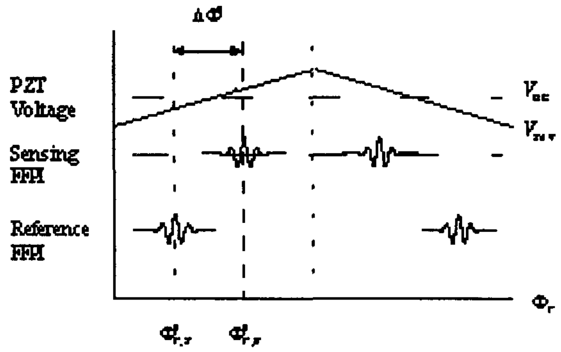

FIG. 2. Outputs of sensing and reference FFPI.

of a Mach-Zehnder Interferometer (MZI). The only moving parts employed were two PZTs on scanning arms of the MZI. Two photodetector outputs were sampled, digitized and stored using a data acquisition board (National Instrument, AT-MIO-16E-2, high-speed 12 bit MIO DAQ). The light source used in Fig. 1 was Oki OE350S (λ = 1.3 μm) Superluminescent Diode (SLD) purchased from Oki Semiconductor with coherence length $L_C \simeq 26\ \lambda$.

III. ABSOLUTE TEMPERATURE MEASUREMENT

The proposed AFWLI consists of three interferometers, one processing interferometer (MZI) and two FFPIs. One FFPI works as a sensing interferometer exposed to the temperature T_S to be measured and the other FFPI works as a reference interferometer which is protected from environmental disturbances but exposed to the known reference temperature T_R. In this set-up, the MZI is scanned to match its phase to that of the sensing FFPI such that, the MZI and the sensing FFPI are coherently matched and interfered. The processing MZI has two PZTs in its two arms. A constant d.c. voltage V_{DC}(100 ~ 150 V, Fig. 2) is applied to the PZT1 in one arm to coarsely match the OPD of MZI to that of the sensing FFPI. And an alternating ramp voltage V_{SAW} (Fig. 2) is applied to PZT2 in the other arm to scan the processing interferometer so that path difference between two arms of MZI L_P can be varied in a certain range as shown in Eq. (1)

$$L_P - \Delta L_1 < L_P < L_P + \Delta L_2 \tag{1}$$

where ΔL_1, ΔL_2 are the arbitrary positive quantities which denote the path length decrement and increment respectively due to the alternating ramp voltage V_{SAW} applied to PZT2 in Fig. 1. Then the OPD of the MZI is given by

$$\Phi_P = \frac{2\pi n L_P}{\lambda} \tag{2}$$

where n is the refractive index of the optical fiber core. Now, assume that the known temperature of the sensing FFPI and the reference FFPI are T_S^0, T_R^0 respectively. When the OPD of the MZI, Φ_P is exactly matched to that of the sensing FFPI, the output of the sensing FFPI is maximized (zero-order fringe peak) at a certain $\Phi_{P,S}^0$ (Fig. 2). where

$$\Phi_{P,S}^0 = \frac{2\pi n L_{P,S}}{\lambda} = \frac{2\pi n L_S}{\lambda} \tag{3}$$

and L_S is the round trip path difference of the sensing FFPI. By the same token, the reference FFPI will give its own zero fringe order fringe peak at a certain $\Phi_{P,R}^0$ (Fig. 2) where

$$\Phi_{P,R}^0 = \frac{2\pi n L_{P,R}}{\lambda} = \frac{2\pi n L_R}{\lambda} \tag{4}$$

and L_R is the round trip path difference of the reference FFPI.

Then, we can get the known value of the (absolute) phase difference $\Delta\Phi^0 = \Phi_{P,S}^0 - \Phi_{P,R}^0$ (this is possible by the proposed signal processing algorithm in reference [4]) rather than identifying $\Phi_{P,S}^0$ and $\Phi_{P,R}^0$ individually and mapping $\Delta\Phi^0 = \Phi_{P,S}^0 - \Phi_{P,R}^0$ to the temperature T_S^0. When a sensing FFPI is exposed to another temperature T_S^i, the phase change induced by the temperature shift $\Delta T_S^i = T_S^0 - T_S^i$ of the sensing FFPI is given by [5]

$$\Delta\Phi_S^i = \frac{2\pi}{\lambda}\left(\frac{n}{L_S}\frac{dL_s}{dT} + \frac{dn}{dT}\right)\Delta T_S^i L_S \tag{5}$$

neglecting the temperature-induced change in the optical fiber diameter. Then the phase of the processing interferometer will have its zero order fringe peak at

$$\Phi^i_{P,S} = \Phi^0_{P,S} = \Delta\Phi^0_S \tag{6}$$

But phase $\Phi^i_{P,S} = \Phi^0_{P,R}$ as the reference interferometer is protected from environmental disturbances and phase difference

$$\begin{aligned}\Delta\Phi^i &= \Phi^i_{P,S} - \Phi^i_{P,R} \\ &= \Phi^i_{P,S} - \Phi^0_{P,R} \\ &= \Phi^0_{P,S} + \Delta\Phi^i_S - \Phi^0_{P,R} \\ &= \Delta\Phi_0 + \Delta\Phi^i_S \end{aligned}\tag{7}$$

is mapped to the temperature T^i_S. By repeating this procedure for the other temperatures T^j_S, all the Φ^j's are mapped to the all the sensing FFPI temperature T^j_S. Applying the same assumption mentioned above for Eq. (5), the phase change $\Delta\Phi^i_P$ induced by axially-straining the fiber on the PZT can be given by [6]

$$\Delta\Phi^i_P = \frac{2\pi}{\lambda}\left(\frac{n}{L_P} + \frac{dn}{dL_P}\right)\Delta L_P L_P \tag{8}$$

But note that $\Phi^i_{P,S}$ in Eq. (6) can be also expressed as

$$\Delta\Phi^i_{P,S} = \Phi^0_{P,S} + \Delta\Phi^i_P \tag{9}$$

because the phase change $\Delta\Phi^i_S$ in Eq. (6) is compensated by the phase change $\Delta\Phi^i_P$ in Eq. (9). So we can equate these two terms $\Delta\Phi^i_s$, $\Delta\Phi^i_P$ by considering only dominant terms of Eq. (5) and Eq. (8)

$$\frac{2\pi}{\lambda}\left(\frac{dn}{dT}\right)\Delta T_S L_S = \frac{2\pi}{\lambda}\left(\frac{n}{L_P}\right)\Delta L_P L_P \tag{10}$$

which results in

$$\Delta L_P = \frac{dn}{dT}\frac{L_P}{n}\Delta T_S \tag{11}$$

From Eq. (11) it is shown that temperature change in the sensing FFPI has a linear relation with the length change in the processing interferometer ΔL_P. The phase difference $\Delta\Phi^i$ between the reference FFPI and the sensing FFPI is linearly and uniquely mapped to the absolute temperature ΔT^i_S over the range in which the linearity assumed in Eq. (5) and Eq. (8) is effective. So, at any temperature T^i_S, $\Delta\Phi^i$ is identified using the signal processing algorithm recently proposed by the author [4]. Then

$$\Delta\Phi^i = \Phi^i_{P,S} - \Phi^i_{P,R} \tag{12}$$

is mapped to the (absolute) temperature T^i_S. This kind of sensor is self-calibrating and is capable of absolute temperature measurement. And also this kind of sensor is not limited by the quadrature stabilization, fringe counting problem. Other desirable features include large dynamic range, while the limitation is that the reference interferometer has to be kept independent of the measurand. Dynamic range of the measurement depends on the dynamic range of the sensing FFPI and the scanning MZI. An FFPI temperature sensor with internal mirror was tested from -200 to 1050 °C [7]. Using high voltage PZTs a total scanning range of 150 μm is possible [8] which approximately corresponds to 115 fringes or 690 °C temperature change for an FFPI sensor of 10 mm cavity length.

IV. EXPERIMENTAL RESULTS

1. Experimental arrangement

Experiments were carried out to demonstrate the performance of the proposed signal processing algorithm for absolute temperature measurement. Before the measurement, one arm of the AFMZI was randomly twisted between two fingers so that the visibility of whole fringe data was maximized on the oscilloscope screen and the twisted arm of the AFMZI was taped and fixed to one side wall-surface of the AFMZI enclosure. The whole system was stabilized for approximately four hours at room temperature after the system was turned on until the drifts of the WLI signal are not visually noticeable on the oscilloscope screen.

TABLE 1. Phase delay $\Delta\Phi^i$ of stability test.

Fringe scan number	Phase delay [sample]	Statistics [sample]
1	54.10853	
2	54.14474	
3	54.10854	
4	54.07233	
5	54.03616	
6	54.89157	
7	54.78320	
8	55.18052	
9	53.56683	
10	53.56690	Mean:
11	53.53082	53.76878
12	53.46905	Standard Dev.:
13	53.36068	0.579 (0.015 fringe)
14	53.28855	
15	53.18020	
16	53.14413	
17	53.14413	
18	54.71174	
19	54.60360	
20	53.14407	
21	53.10804	

TABLE 2. Phase delay $\Delta\Phi^i$ of absolute temperature measurement.

Sensing FFPI Temp. [°C]	Phase delay [sample]	Statistics [sample]
24	−7.223328	
24	−7.248166	Mean: −7.22836
24	−7.223475	Standard Dev.: 0.0110 (0.0004 fringe)
24	−7.223486	
24	−7.223417	
25	−11.47066	
25	−11.47117	Mean: −11.46902
25	−11.47101	Standard Dev.: 0.0043 (0.0001 fringe)
25	−11.47105	
25	−11.46120	
26	−15.70248	
26	−15.70258	Mean: −15.68752
26	−15.67775	Standard Dev.: 0.0136 (0.0005 fringe)
26	−15.67764	
26	−15.67766	
27	−19.80177	
27	−19.80181	Mean: −19.79668
27	−19.77718	Standard Dev.: 0.0109 (0.0004 fringe)
27	−19.80161	
27	−19.80165	

2. Stability test

First, the stability of the signal processing algorithm was tested. For this purpose the sensing FFPI and reference FFPI were placed together side-by-side (but not touching each other) between styrofoam substrates enclosed by an aluminum box so that both sensing and reference FFPIs are exposed to the same room temperature. After approximately 4 hours of stabilization, 21 fringe scans were collected with a 10

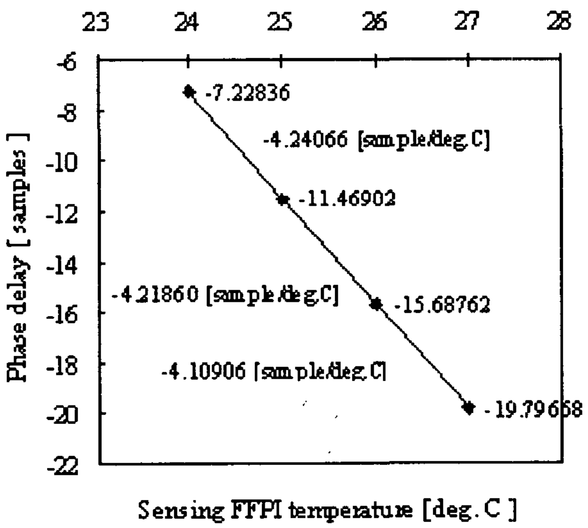

FIG. 3. Phase delay fall-off in absolute temperature measurement.

minute separation. Sampling rate was 36 samples/fringe, PZT scanning period was 33 msec and fine tuning step was 1/1000 fringe. The fine tuning step is the signal processing parameter used in reference [4] to enhance the accuracy of $\Delta\Phi^i$. In the stability test $\Delta\Phi^i$was measured in terms of the total number of samples between $\Phi^i_{P,S}$ and $\Phi^i_{P,R}$. For example, if there are 36 samples in the range between $\Phi^i_{P,S}$ and $\Phi^i_{P,R}$, then $\Delta\Phi^i$ has the value of 36 samples which corresponds to 2π phase delay (or one fringe) not considering the sign of the phase delay. Table 1 shows the phase delay between the sensing FFPI and the reference FFPI. In these measurements the true phase delay $\Delta\Phi^i$ between the sensing FFPI and reference FFPI was not known and the standard deviation (S.D) of the phase delay was calculated instead of the RMS error. Statistics in Table 1 show that the proposed signal processing algorithm calculated the phase delays of 21 fringe scans with a standard deviation of 0.579 sample which is 0.015 fringe. Standard deviation of 0.015 fringe corresponds to 0.09 °C of accuracy for an FFPI sensor of 10 mm cavity length [9].

3. Absolute temperature measurement

The second experiment shows an example of absolute temperature measurement. The temperature of the reference FFPI was maintained at 24 °C using a thermo-electric cooler (TEC) and the temperature of the sensing FFPI was varied from 24 °C to 27 °C using another TEC. WLI fringe scans were measured at the intervals of 1 $^{c}ircC$ for the sensing FFPI. Sample rate was 25 samples/fringe and PZT scan period was $\sim$ 9 seconds. Table 2 shows the mean and the standard deviation of the temperature measurement in terms of sample. Five measurements were collected in a row at fixed sensing FFPI temperature. In this case the proposed signal processing algorithm repeatedly produced identical $\Delta\Phi^i$ at fixed sensing FFPI temperature. Note that the fine tuning step was set as 1/1000 fringe and ±0.0005 fringe (half the fine tuning step) was the lowest obtainable fine tuning resolution. The resolution of approximately 0.0005 fringe was obtained with one exception. That is the standard deviation 0.0001 fringe of five measurements (25 °C sensing FFPI temperature) in Table 2. Fig. 3 shows the phase delay increase between temperature measurements.

Note that the difference of mean phase delay between temperature measurements (slope of straight line segment in Fig. 3) was −4.24066, −4.21860, and −4.10906 samples/°C and the temperature dependence of these phase delays between temperature measurement was almost constant (linear) as assumed in Eq. 5 and Eq. 8. Slope fell off by 0.13 samples (0.39 samples) over the 2 °C (6 °C or one fringe) temperature change and this was presumably due to the imperfect linear expansion of the PZT.

V. CONCLUSIONS

In 1994 Kaddu demonstrated the WLI absolute temperature measurement system over the temperature range of 20–70 °C. But, in this scheme the Fabty-Perot type scanning interferometer was formed by a cleaved end of a single mode fiber and a planar mirror, which is driven by a computer-controlled Nanomover (micropositioning system) [10]. The feasibility of absolute temperature measurement using all fiber white light interferometry was demonstrated in this report. The author believes the measurement in this report to be the first time-domain absolute temperature measurement using all fiber white light interferometry. The previously proposed signal processing algorithm has proven to be capable of measuring the phase difference $\Delta\Phi^i$ between $\Phi^i_{P,S}$ and $\Phi^i_{P,R}$ obtained from the all fiber white light interferometry temperature measurement system. In the stability test, the signal processing algorithm repeatedly produced identical $\Delta\Phi^i$ with a resolution of 0.015 fringe at fixed sensing FFPI temperature. And the absolute temperature measurement test showed that the white light interferometry absolute temperature measurement system was capable of obtaining a theoretical minimum detectable change (0.0005 fringe) which is consistent with the performance prediction in report [4].

ACKNOWLEDGMENTS

The author acknowledges the support of Hansei University in this work.

REFERENCES

[1] H. C. LeFerve, in *Proceedings of 7th Optical Fibre Sensors Conference '90*, 345 (1990).
[2] K. T. V. Grattan, B. T. Meggitt (ed.), *Optical Fibre Sensor Technology* (Chapman & Hall, London, 1995).
[3] S. Chen *et al.*, Appl. Opt. **31**, 6003 (1992).
[4] J. G. Kim, Journal of the Korean Sensors Society **9**, 316 (2000).
[5] E. Udd (ed.), *Fiber Optic Sensors* (Wiley Interscience, New York, 1991).
[6] G. B. Hocker, Appl. Opt. **18**, 1445 (1979).
[7] C. E. Lee, R. A. Atkins, and H. F. Taylor, Opt. Lett. **13**, 101 (1988).
[8] K. Weir, K. T. V. Gratten, and A. W. Palmer, Proc. SPIE **2248**, 307 (1994).
[9] J. H. Lee, *"A Novel Signal Processing Algorithm for FFPI and its sensor system application,"* Ph.D. dissertation, Texas A & M University, College Station, Texas, 1994.
[10] S. C. Kaddu, S. F. Collins, D. J. Booth, in *Australian Conference on Optical Fibre Technology '94*, 150 (1994).