# Single - Crystal Sapphire Optical Fiber Sensor Instrumentation

**Annual Report**

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## Disclaimer

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# Abstract

In this research program, several optical instruments for high temperature measurement based on single crystal sapphire material are introduced and tested for real-time, reliable, long-term monitoring of temperatures for coal gasifier. These are sapphire fiber extrinsic Fabry-Pérot interferometric (EFPI) sensor; intensity-measurement based polarimetric sapphire sensor and broadband polarimetric differential interferometric (BPDI) sapphire sensor. Based on current evaluation and analysis of the experimental results, the broadband polarimetric differential interferometric (BPDI) sensor system was chosen for further prototype instrumentation development. This approach is based on the self-calibrating measurement of optical path differences (OPD) in a single-crystal sapphire disk, which is a function of both the temperature dependent birefringence and the temperature dependent dimensional changes. The BPDI sensor system extracts absolute temperature information by absolute measurement of phase delays. By encoding temperature information in optical spectrum instead of optical intensity, this sensor guarantees its relative immunity to optical source power fluctuations and fiber losses, thus providing a high degree of long-term measurement stability which is highly desired in industrial applications.

The entire prototype for BPDI system including the single crystal sapphire probe, zirconia prism, alumina extension tube, optical components and signal processing hardware and software have shown excellent performance in the laboratory experiments shown in this report.

# 1. Introduction

Based on the research works covered by previous annular reports, an improved versions of the broadband polarimetric differential interferometric (BPDI) sensor for high temperature measurement, named as broadband polarized-light interferometric (BPLI) sensor in last annular report, has been designed and tested. With one single crystal sapphire disk with 0.13inch thickness as the sensing element, the temperature sensor achieve a wide dynamic range over 1600ºC with an accuracy better than 0.25% compared to B-type thermocouple, and resolution of 0.07 ºC of the full measurement scale. The structure of this sensor is simple and cost-effective for high temperature sensing, and is also designed to be robust enough to survive in real engineering environments.

In this report, the research works are mainly focused on three parts:

First, the system setup is optimized, which is more close to a field-ready prototype, laboratory test out and calibration were done.

Second, the signal processing algorithm used to do the signal demodulation and gap value calculations in computer is modified, which provides the capability to do stable, high performance signal processing for long-term run.

Third, systematic evaluation on the system is done, which include the long-term stability measurement, resolution evaluation, self-calibration tests, very promising data are obtained.

# 2. BPDI system setup optimization

## *2.1 Brief review on the BPDI system sensing priniciple*

Single crystal sapphire exhibits an inherent birefringence based on its inner atomic arrangement of the crystal structure. In this system, a single-crystal sapphire disk is sandwiched in a polarimeter formed by a polarizer and an analyzer with their polarization directions parallel to each other. Since both the birefringence and thickness of the sapphire disk are functions of temperature, the state of polarization (SOP) of the input light beam is then modulated by temperature changes through the sapphire diskand this modulation is also a function of the light wavelength. The output optical spectrum monitored by a spectrometer therefore contains real-time temperature information from the location of the sapphire disk.

Figure. 1. illustrates the working principle of the sensor head. A single-crystal sapphire disk with inherent birefringence is sandwiched between a polarizer and an analyzer, whose polarization directions are parallel to each other and along the z-axis direction. The principle axes (i.e.f-axis and s-axis) of sapphire disk are oriented at $45^o$ with respect to the z-axis direction. Due to the birefringent nature of the sapphire material and the thickness (d) of the sapphire disk through which the light passes, input light beams that are polarized along f(ast)-axis and s(low)-axis directions will propagate with differential phase delays. The output light spectrum from the polarization analyzer (P2) is a result of the interference between those light beams with phase delays. Therefore, interference fringes are generated which contain the phase-delay information and these in turn are the signatures of temperature. By encoding and decoding temperature information in the phase of an optical signal, this sensor design provides the self-calibrating capability, where that encoded temperature data is not corrupted by optical source power fluctuations and fiber losses.

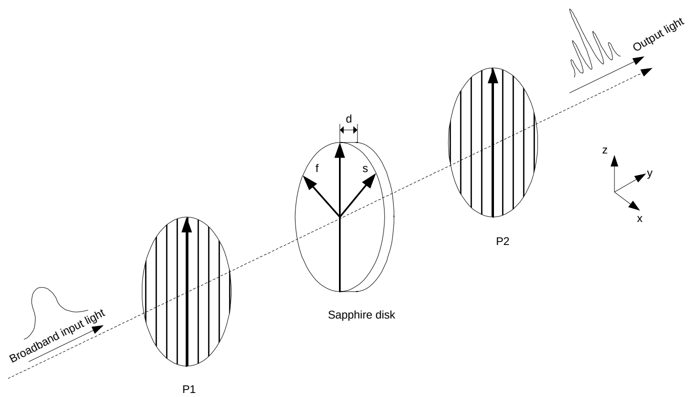



Fig. 1. A conceptual schematic design of sensing head: broadband polarimetric differential interferometry (BPDI)

Mathematically, the transmitted interference spectrum signal from the polarimeter shown in Figure 1. can be expressed as:

$$I(\lambda) = 2kI_s(\lambda) \quad (1 + \cos(\frac{2\pi d(T)\Delta n(T)}{\lambda})) \qquad (1)$$

Where $I_s(\lambda)$ is the spectral power distribution as a function of the wavelength ($\lambda$) of the broadband input light source; *k* is a parameter describing the power loss of the optical system, and can be treated as a constant (0<k<1); d is the thickness of the sapphire disk; and $\Delta n = n_e - n_o$ is the birefringence between the extraordinary ray and the ordinary ray determined by crystallographic orientation of the atomic structure of the sapphire disk. Both d and Δn are functions of temperature T.

Ideally, the interference fringes would form a perfect sinusoidal curve if plotted in wave numbers after it is normalized with respect to $I_s(\lambda)$ according to Equation (1):

$$I(\lambda) = 2k(1 + \cos(\frac{2\pi d(T)\Delta n(T)}{\lambda})) = 2k(1 + \cos(\frac{2\pi f(T)}{\lambda})) \qquad (2)$$

where,

$$f(T) = d(T)\Delta n(T) \qquad (3)$$

From the detected optical spectrum out from the polarimeter, an internally developed algorithm is employed to measure the difference of optical paths $f(T)$ between the two orthogonal linearly polarized light beams in the sapphire disk, which is uniquely related to the differential phase delay between the two orthogonal polarized light beams. The algorithm used to calculate $f(T)$ is modified compared to previous work, and will be described in the following section.

## *2.2 Experimental setup*

The transmission spectrum from the polarimeter is measured according to the basic working principle illustrated in the previous section . To fabricate a portable minimized temperature-sensing probe, one right angle prism made of zirconia is employed to reflect light back at the end of the sensing tube. By detecting the reflected optical signal instead of transmitted optical signal, the structure of the sensing head is simplified and all components are fitted into a solid tube, one polarizer and one light collimator are saved, the measurement sensitivity is also doubled by causing the light beam to pass through the sensing element twice.

In radiation thermometry technologies, the blackbody radiation is used directly to measure temperatures, while in this sensor system, it is superimposed as background on the interference fringes used for temperature measurements, and become increasingly stronger with the increasing of temperature, which will degrade the accuracy of optical interference fringes measurement, and in turn affect the accuracy of the temperature measurement. As plotted in Figure. 2, at relatively low temperatures, the effect of the blackbody radiation is negligible while at high temperatures, the effect of the blackbody radiation becomes more apparent and is the most influential at temperatures over 1000 $^{o}$C. In order to minimize the influence of the blackbody radiation background, especially for the situation of temperature over 1000 $^{o}$C, a digital signal generator is used to modulate the LED output light. Since the background from the blackbody radiation is essentially a direct component (DC) signal, modulated optical signals from the optical source become alternating component (AC) signals, which are temperature signatures. The blackbody background is thus reduced substantially. Modulation of the optical source makes it possible to measure temperature as high as the stability of the sapphire material will allow ,even blackbody radiation exist and become stronger as temperature increases.

A complete schematic design of the high temperature optical sensor using a single-crystal sapphire disk based on the BPDI technology is shown in Fig. 3.  Fig. 4 shows an overview of the actual system setup.

The broadband light from a high power light emitting diode (LED), whose center

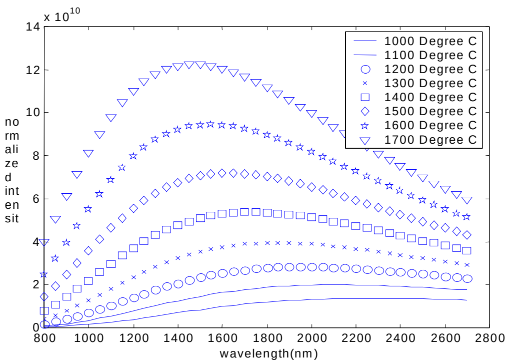



Fig 2(a). Theoretical results of blackbody radiation at different temperatures

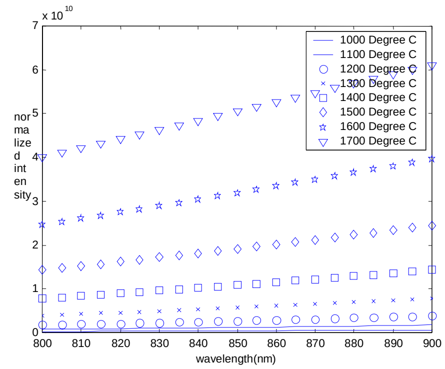



Fig 2 (b). Theoretical results of blackbody radiation at different temperatures, for the interested wavelength range( 800nm~900nm)

wavelength is 850nm and spectral covers from 810nm to 890nm, is injected into a 2m lead-in multimode optical fiber and propagates through a two by two fiber coupler to the sensor head. The polarizer used in this system is an optical grade calcite Glan-Thompson polarizing prism from Melles Griot. The light is first converted into a linearly polarized collimated optical beam by a graded-index lens and travels across a free space enclosed by a high temperature ceramic tube and a single crystal sapphire tube to a single crystal sapphire disk (with thickness 3.27mm and diameter 25mm). The sapphire disk functions as the temperature-sensing element. The sapphire disk is arranged such that the input linear polarization direction of the light is at 45 degrees with respect to the fast and slow axes of the crystal. After passing through the sapphire disk, the two linear polarized light components along the fast and slow axes experience a differential phase delay due to the sapphire birefringence and its thickness as described above. The light, containing the two orthogonally linear polarized light components, is then reflected by a right angle zirconia prism and passes through the sapphire-sensing element again, doubling the differential phase retardation. Since the right-angle zirconia prism has no birefringence because of its cubic crystallographic structure, no additional differential phase delay will be induced in the detected optical signals. The two linear polarized light components with a differential phase delay are combined along the polarizer direction to interfere with each other, when light exists the polarimeter. The output light from the polarimeter is then collected by the same input optical fiber and travels back along the same fiber and through the same coupler to the optical detection end, which contains a fiber optic PC plug-in spectrometer (USB2000 from Ocean Optics, Inc.), composed of a grating and a CCD array. The intensities of the dispersed spectral components of the signal are scanned electronically by the CCD array. Additional signal processing is performed in the computer. An Omega type B (6%RH-Pt) high-temperature thermocouple was used as the temperature monitor for reference. The sensor was heated in a high temperature furnace up to 1600 $^{o}$C (manufactured by Deltech Inc).

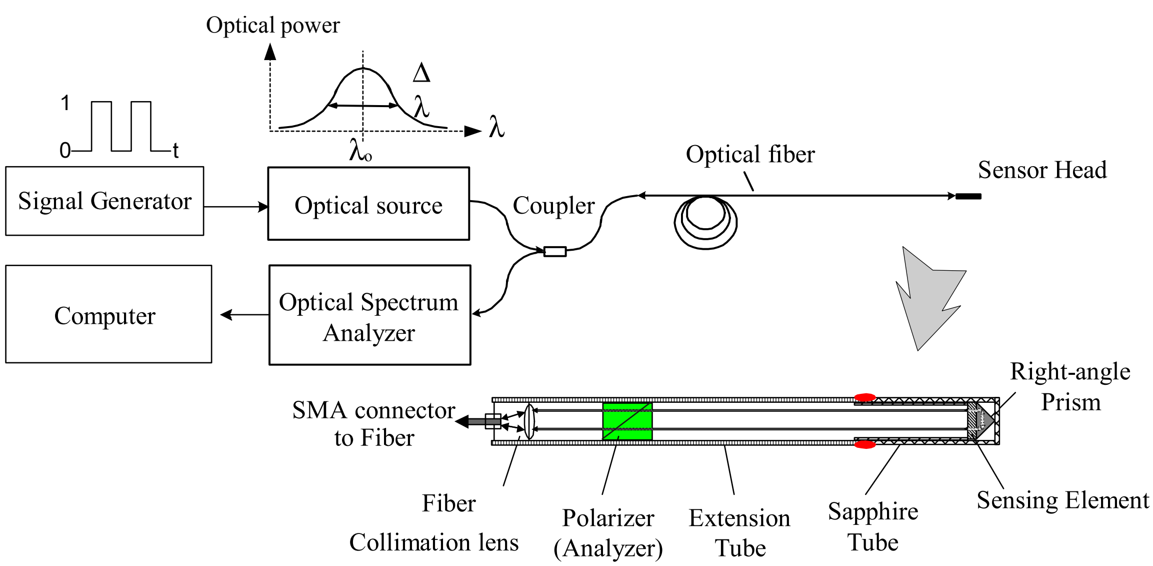



Fig. 3. Schematic design of the single-crystal sapphire based optical high temperature sensor

Fig. 4. Overview of the sensing system

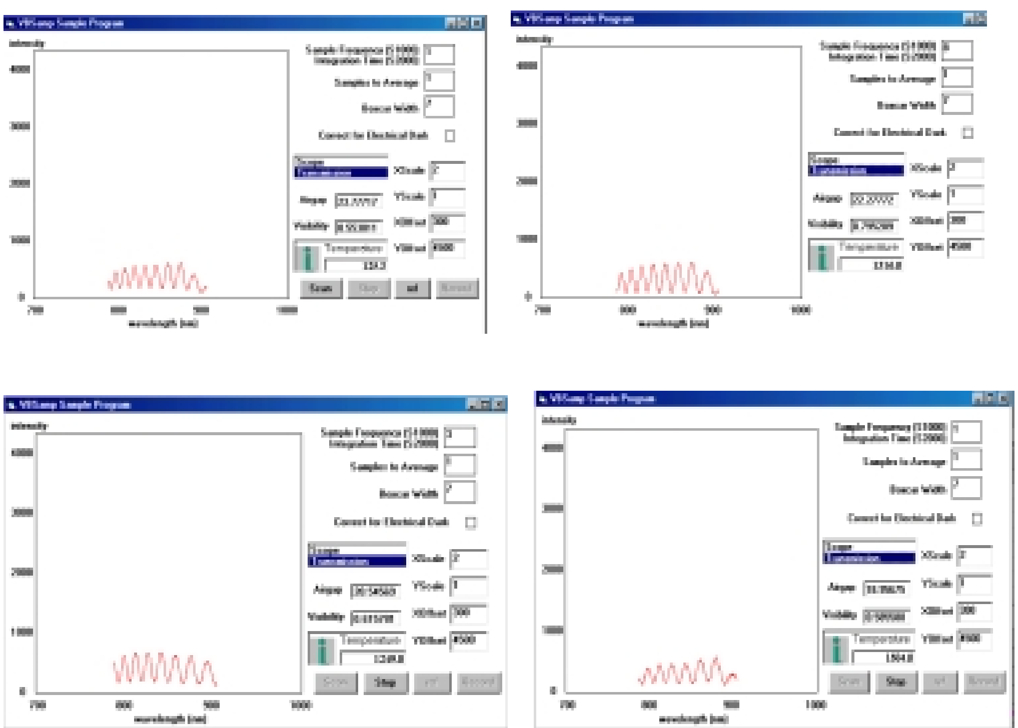


Fig. 5. Spectrum measurement result

# 3. Algorithm for optical signal processing

As one of the most sensitive measurement systems, optical interferometry has been used in a variety of applications. In most of the conventional mono-wavelength interferometric systems, a coherent light source was used to achieve a large coherent length, which in turn gives out a large dynamic range. For this kind of system, the most commonly used signal demodulation method is peak counting, i.e. using a power meter to detect the intensity of the interference signal from the sensor head and an electric counter to count the total number of peaks from a reference point. Obviously, only relative measurements can be achieved by this method. Another disadvantage of this method is the lower resolution, which is about the same order as the source wavelength. Although some improved methods have been developed, it has been difficult to achieve both large dynamic range and high resolution and absolute measurement in same system.

White light or low coherence interferometry is a technique, which dates back to 1913 and was reapplied to optical fiber sensing in 1983. Instead of using a highly coherent light source, a broadband light source, such as an LED, is used. Although the power-detection approach can be used, to fully exploit the advantages of the white light system, spectrometer-based detection systems are more popular.

The white light interferometric system inherits most of the advantages from the conventional interferometer, such as immunity to the light source power drift and changing of transmission losses, high resolution, large dynamic range, etc. On the other hand, by using the spectral domain signal processing technology, an absolute measurement of the distance between the interfering interfaces can be realized.

Considering the industrial applications, the use of a long life, low priced broadband light source (such as LED) improves the stability of the whole system and decrease of the price dramatically. Numerous applications of white light interferometric sensor systems have been reported, covering a wide range from single point measurement to distributed sensor systems .

In this research, a novel data processing method for white light interferometric system, which can improve system resolution dramatically, is introduced. A compact white light signal-processing unit based on this algorithm has been setup, and a sub-nm resolution has been demonstrated. In addition, by using a self-compensating data processing method, high temperature stability has been achieved.

## *3.1 Existing data processing methods*

Various methods have been developed to demodulate the air-gap *G* from the normalized interference spectrum, which is described by equation (2) in section 2. Most of these kinds of algorithm can be categorized into two classes. The first class can achieve high resolution (which mainly depends on the resolution of spectrometer), but the dynamic range of air-gap must be limited to the half wavelength range to avoid the problem of ambiguity in signal interpretation due to the periodic nature of the signal. The second class can achieve a large dynamic range but suffers from low resolution. The basic ideas for these methods are introduced briefly as follow:

***Class one:***

Type one is based on tracing a special point in the interference spectrum (such as peak point or valley point). Then from the wavelength of this special point, the value of air-gap can be demodulated. The following calculation is based on peak tracing:

The wavelength $\lambda_m$ of a peak point in interference spectrum satisfies

$$\frac{4\pi G}{\lambda_m} + \varphi_0 = m2\pi \qquad (4)$$

Where the spectral order $m$ is a non-negative integer.

Equation (4) can be transformed into:

$$\begin{aligned} G &= \frac{(m2\pi - \varphi_0)\lambda_m}{4\pi} = \frac{K_m}{2}\lambda_m \\ K_m &= \frac{(2m\pi - \varphi_0)}{4\pi} = m - \frac{\varphi_0}{2\pi} \end{aligned} \qquad (5)$$

Obviously, for a given peak point, the value of $K_m$ is a constant.

To demodulate the air-gap $G$ from a special peak wavelength $\lambda_m$, $K_m$ must be acquired first. The identification of the interference order $m$ is so difficult that the unambiguous operating range of the air-gap is limited in only half of the source wavelength.

The resolution of the measurement is mainly dependent on the resolution of spectrometer. From equation (5), the relative error of this system induced by the spectrometer can be described as

$$\left|\frac{\Delta G}{G}\right| \cong \left|\frac{\Delta \lambda}{\lambda}\right| \quad (6)$$

***Class Two:***

To realize absolute measurement in a large range, at least two special points in the interference spectrum need to be used. Suppose $\lambda_1$ and $\lambda_2$ ($\lambda_1>\lambda_2$) are the wavelengths of two adjacent peak points in the interference spectrum, their interference orders are $m$ and $m+1$.

From equation (4),

$4\pi G/\lambda_1 + \varphi_0 = m2\pi$ ;

$4\pi G/\lambda_2 + \varphi_0 = (m+1)2\pi$

The air-gap $G$ can be demodulated from:

$$G = \frac{\lambda_1 \cdot \lambda_2}{2(\lambda_1 - \lambda_2)} \quad (7)$$

Obviously, this method overcomes the ambiguity problem of class one. The dynamic range is only limited by the coherence length of the white light system.

From equation (7), the relative error induced by the spectrometer is

$$\left|\frac{\Delta G}{G}\right| \cong \sqrt{2}\left|\frac{\lambda_2}{\lambda_1 - \lambda_2}\right| \bullet \left|\frac{\Delta \lambda_1}{\lambda_1}\right| \quad (8)$$

Comparing equation (6) with equation (8), in class two type signal processing algorithm, the relative error induced by the spectrometer will be enlarged by a factor of $\sqrt{2}\left|\lambda_2/(\lambda_1 - \lambda_2)\right|$. In our system, the central wavelength of the light source (LED) is

850nm. In the normal operating range (air-gap 5-15 μm), this factor is about 15—50, which means the resolution of type two is much lower than class one signal processing techniques.

### *3.2 New Algorithm*

To combine the advantages of these two kinds of methods together, we developed a novel data processing method, which can realize both high resolution and a large dynamic range simultaneously.

The basic idea of this method is: use wavelengths of two adjacent peak points in the interference spectrum to get a rough air-gap value from equation (7) (large dynamic range is achieved); this rough air gap value will be used to determine the order number *m* and a rough $K_m'$ value for one of the two peak points (equation (5)). Then, by using a calibrated *K* stored in the computer, an accurate $K_m$ can be recovered from the rough $K_m'$; Using equation (5) again, the accurate air gap value can be calculated from the accurate $K_m$ and the peak wavelength (therefore, high resolution is achieved).

The technique used here to recover the accurate $K_m$ from the rough $K_m'$ value is presented as follows:

In equation (5), although $K_m$ is not an integer, for a given peak, it is a constant. And for adjacent peaks, the difference in $K_m$ is 1. For example, if the $K_m$ of one peak is 12.34, then, for the other peaks, the $K_m$ will be 13.34, 14.34, 15.34…and 11.34, 10.34, 9.34… and so on.

By calibration, the $K_m$ value for a special peak ($K_m^0$) can be acquired and stored in the computer. During the process of measurement, when the rough $K_m^{'}$ value for the peak has been acquired, although we don't know the order $m$ of this peak point, the difference between $K_m$ and the stored $K_m^0$ should be a integral number. So, the accurate $K_m$ can be calculated by adding $K_m^0$ with the integer part in the difference between the rough $K_m$ and $K_m^0$.

$$K_m = K_m^0 + INT(K_m^{'} - K_m^0 + 0.5) \qquad (9)$$

Where, function *INT (…)* means to obtain the integral part.

Another approach for recovering the accurate $K_m$ value from the rough $K_m^{'}$ value is: calibrate $K_m$ for all the peak points that will be used in the whole dynamic range and store them in the computer; during the process of measurement, when a rough $K_m^{'}$ value is acquired, the closest $K_m$ stored in the computer will be chosen as the accurate $K_m$.

Both approaches have been realized in the Visual Basic environment, with the second one producing a more robust performance. The experimental results are presented in the following section.

# 4. Experimental results

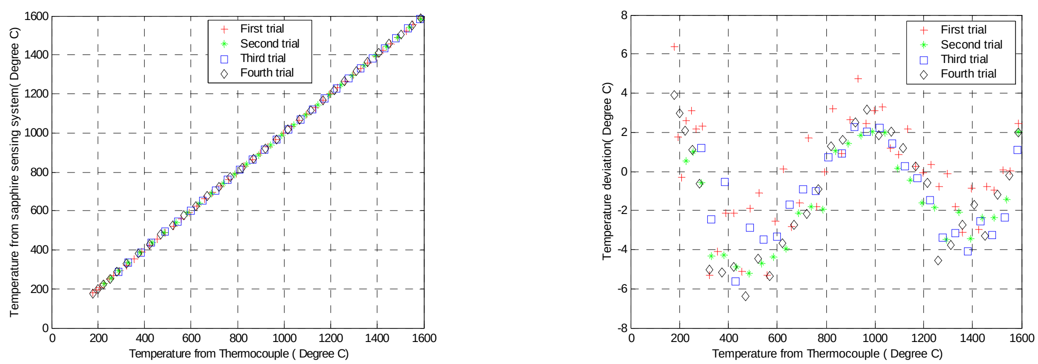
One typical reflected light spectrum from the sensing head is shown in Fig. 5. Based on the optical spectrum measured by the optical spectrometer, the real-time temperature information can be obtained in the computer through the calibrated relationship between the temperature values and the "gap" values, i.e. the $f(T)$ values from Equation (4).

### *4.1 Precise measurements*

Precise measurements were performed to characterize the reproducibility of the measurements by the BPDI optical temperature measurement system. Four experiments were conducted to determine the repeatability of the temperature measurements. Fig. 6 provides the results of the temperature measurements repeated seven times up to 1600$^{o}$C. Fig. 6 (a) demonstrates the exceptional repeatability of the temperature measurements, and Fig. 6 (b) shows the deviation of the measurement results from the BPDI sensor system with those of the B type thermocouple, which was used as the temperature reference. For temperature over 1000$^{o}$C, an accuracy of ±4$^{o}$C relative to the B type thermocouple was achieved for repeated temperature measurements, which represents 0.25% of the full measurement scale.

### *4.2 Longterm stability tests*

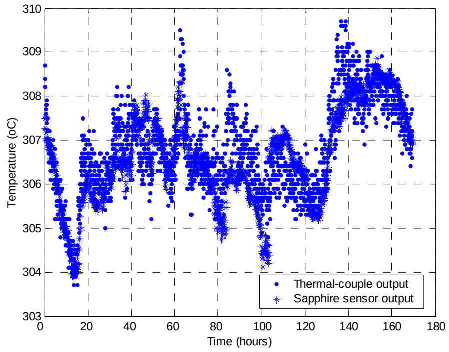
In industrial field environments, sensor performance parameters such as reduced requirements on accurate optical alignment, insensitivity to vibrations, and ease of installation , which are generally required by most applications, can not be easily met by current optical sensors. The BPDI optical temperature measurement system design takes advantages of both optical fibers and bulk optics to meet those requirements for field applications. Bulk optics is convenient for reducing the required tolerances on optical alignment and also for reducing the senstivitty to vibration.  The optical fiber can transmit light for a long distance with small attenuation and is easily implemented in industrial environments because of its small size, light weight and immunity to electromagnetic interference (EMI).



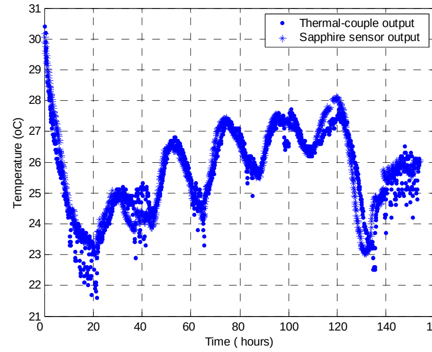

(a) (b)

Figure 6: (a) BPDI sensor temperature measurement versus thermocouple temperature measurement
(b) Deviation of BPDI temperature from thermocouple temperature

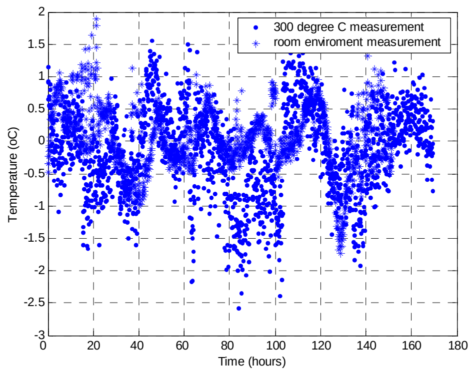
The results of the long term stability tests are shown in Fig. 7. These experiments were carried out for different temperature environments.  The results for  room temperature stability testing are shown in Fig. 7a, and the results for 300$^{o}$C in Fig. 7b.  As shown in this figure, the long-term performance of the BPDI optical temperature measurement system is comparable to the thermocouple performance. Fig. 7 (c) shows the temperature differences between the thermocouple and the BPDI system for a time duration of over 150 hours.  The results show the maximum deviation is in the range of ±2 $^{o}$C. Fig. 7 (d) shows the performance degradation of thermocouple for a long term run at 1200 $^{o}$C, while optical thermometer performs well because of the optical materials survivability.



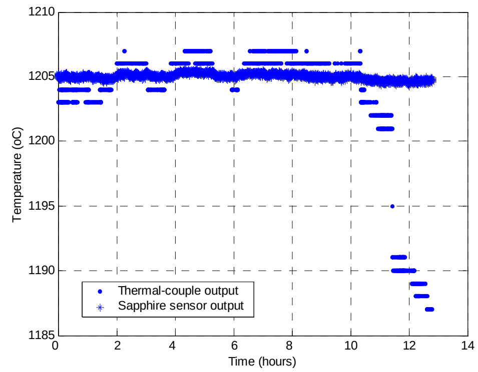

(a) At 306$^o$C




(b) At 26 $^o$C




(c ) Temperature deviation between thermocouple and optical thermometer



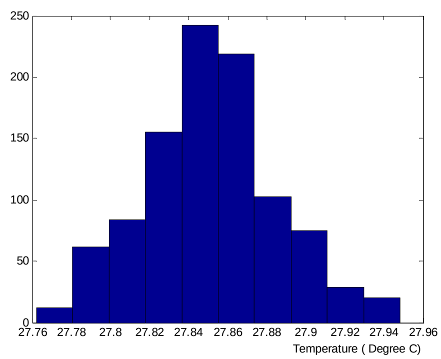

(d) At 1205 $^o$C

Figure 7: Long term stability test results

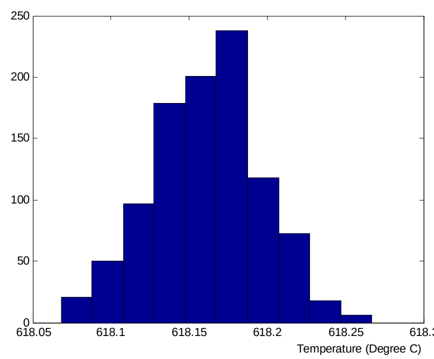
## *4.3 Sensitivity tests*

Interferometric sensors have extremely high sensitivity by detecting the differential phase change of an optical signal. The BPDI system provides resolution better than 0.1$^o$C for a wide dynamic measurement range, which is an advantage over other traditional thermometers, such as thermocouple and optical pyrometers.

In general, the resolution of the sensor system is usually interpreted by the standard deviation of a series of temperature measurements at a constant temperature. It is common to use twice the standard deviation as the direct measure of resolution. The evaluation of the sensor resolution was performed using a calibrated sensor at room temperature and also at 618°C. In the test, 1000 temperature values were acquired continuously and the resulting histogram is plotted in Fig. 8. The standard deviation of the temperature data was calculated to be $\sigma$=0.0348°C and $\sigma$=0.0343°C, respectively. Therefore, the resolution of the sensor system was estimated to be $2\sigma$=0.0696°C and $2\sigma$=0.0686°C. The normalized resolution with respect to the dynamic range of the system was 0.005% of the full scale. Further improvement can be achieved by increasing the resolution for the spectrograph measurement and signal processing algorithm for phase shift recovery in the interferometer.




(a) Room temperature



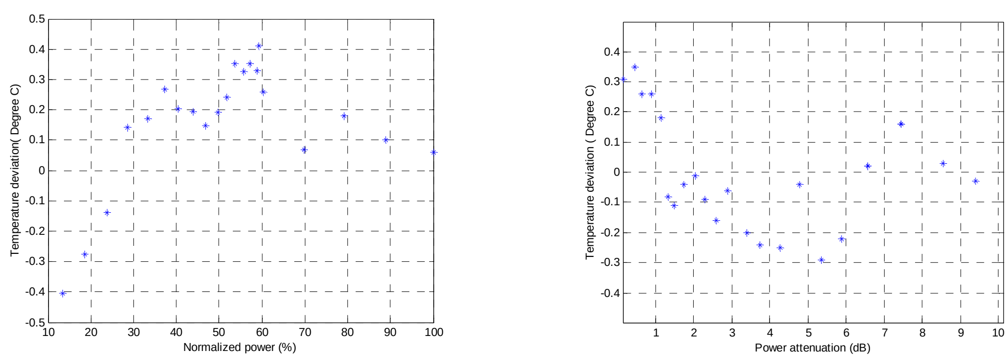

(b) At618.5°C

Figure 8: Histogram of temperature measurement

## *4.4 Self-calibration capability tests*

The BPDI technology extracts temperature information by absolute measurement of the phase shift of orthogonally polarized light, which is attractive for harsh environment applications because of no requiring of initialization and/or calibration when the power is switched on. To make the absolute measurement meaningful, a self-compensating capability is desired so that the optical power fluctuations and fiber loss changes can be fully compensated.

By self-referencing the two orthogonal polarized lights, the BPDI technology posses a self-compensating capability. To evaluate the self-compensating capability of this optical temperature measurement system, the output temperature variations are monitored when the optical source power is changed by changing its driving current. Fig. 9(a) shows the output temperature variations as a function of the normalized optical power of the optical source (LED), as shown, temperature variation range is limited to ±0.45°C for total optical power changes up to 90%. Theoretically speaking, changing the driving current of a semiconductor optical source (LED) would also change the spectrum in addition to the optical power level change, the distortion of the source spectrum would also introduce error to the measurement results through the non-centered filtering effect. Therefore, the measurement results shown in Fig. 9(a) also indicate the contribution from the source spectrum distortion. To evaluate the self-compensating capability of this optical temperature measurement system, the output temperature variations are monitored when the multimode fiber was bent to change the fiber attenuation. Fig.9 (b) shows the temperature variation is in the range of ±0.4°C for fiber attenuation up to 9dB.




(a)BPDI System measured temperature variations as a function of the normalized optical power

(b)BPDI system measured temperature variations as a function of fiber losses

Figure 9: self-calibration capability tests

# 5 Conclusion and future works

In this research work, the broadband polarimetric differential interferometry (BPDI) was chosen for further prototype instrumentation development based on the current evaluation and analysis of the experimental results. This approach is based on the self-calibrating measurement of the optical path length changes in a single-crystal sapphire disk, which is a function of both the temperature dependent birefringence and the temperature dependent dimensional changes. Further optimization of the system design and fabrication of a prototype for continuous operation in a coal gasifier operating under high temperatures and extremely corrosive conditions will be carried out.

By employing single crystal sapphire and fully stabilized cubic zirconia, both of which have high melting temperatures (over 2000 degrees Celsius) and good chemical inertness, BPDI based optical thermometer for coal gasification units has been designed and laboratory tested. Resolution of better than 0.1$^{o}$C and high precision has been achieved over a wide dynamic measurement range from room temperature up to 1600$^{o}$C. Employing a self-calibrating absolute measurement technique of the optical phase shift in a single-crystal sapphire disk, this optical single crystal sapphire temperature measurement system is immune to optical source power fluctuations and fiber losses, providing a high degree of long-term measurement stability, which provide a potential solution for harsh environment industry applications.

The prototype of the broadband polarimetric differential interferometry (BPDI) sensor has been successfully demonstrated in the laboratory. The future work will forcus on system optimization and scale-up for a full field demonstration at Global Energy

Technology's Wabash River Facility, and bring it to a level where the sensor will become commercially viable for the coal gasification industry. The sensor instrumentation will be designed for continuous operation in an actual slagging coal gasifier which operates under high temperatures and extremely corrosive conditions. In detail, the following work will be carried out for future system development:

## *5.1 Optimization of the designed system*

Based on the BPDI technology and results of laboratory tests and calibrations, design of both hardware and software for signal processing will be optimized to improve the performance. A complete prototype sensor instrumentation system will be designed and implemented for reliable and accurate high temperature measurement.In order to accomplish this task, the following steps are to be undertaken:

**1.** Resolutions of the system depend both on the thickness of sapphire sensing element and the resolution of optical spectrum analyzer. Further tests with sapphire disk of different thickness will be done to find the optimal resolution.

**2.** To simplify the signal detecting unit structure, new modulation methods on optical source will be tried to reduce blackbody radiation. The algorithm used to perform the signal demodulation and gap value calculation in computer will be optimized.

**3.** The software will be upgraded for the whole system. By employing Visual_BASic or LabVIEW; a graphical user interface (GUI) will be used to display the data for inspection and the data will also be stored on hard disk for further analysis.

## *5.2 Design and fabrication a field ready prototype sensor system*

A sensing tube prototype, which contains the sensing element and optical reflector, is needed to survive high temperature upto $1600^0C$ when the sensing head is placed physically in the coal gasifier. A single crystal sapphire tube is employed to protect and hold sapphire sensing elements and a right angle zerconia prism, which works as an optical reflector. Integrating sensing head and polarizer/analyzer with fiber collimator to make a compact unit improves mechanical stability. In order to make the final version for this sensing head structure simple and cost-effective for high temperature sensing and robust enough to survive in real engineering environments, the following tasks are carried out:

**Task 1.** Define requirements –the requirements for the system and system integration with the existing gasification facility will be outlined. Before the designed sensing system is installed in the coal gasifier, requirements for temperature of operation position in the gasifier, stages to be instrumented in the gasifier, slagging conditions at the temperature measurement points, length into hot zone, length of refractory, location of electronics, etc. will be specified.

**Task 2.** Design and fabricate a ruggedized sensor system – based upon the requirements generated in the preceding task, the field test ready prototype system will be designed and fabricated.

**Task 3.** Design and fabricate a protective housing – although the corrosion resistance of the single crystal sapphire material has been documented by laboratory testing, special consideration will be given to the required mechanical protection of both the sensor probe and the associated signal demodulation system.

**Task 4.** Laboratory test and calibration – prior to the actual installation of the temperature sensor system in the gasification unit, the entire system will be tested in the laboratory to ensure proper operation.

## *5.3 Field test*

For field test, consideration of the required environmental performance in a slagging gasifier was a prime concern in the design of the optical sensor components, which must physically reside in the gasification unit. According to the properties of the selected materials for sensing head fabrication, it has potential to survive the high temperature harsh environments. High-density polycrystalline aluminum oxide and transformation-toughened zirconium oxide were found to provide the best corrosion resistance out of a very wide range of oxide and non-oxide materials tested. Because of their corrosion resistance, single crystal sapphire and fully stabilized cubic zirconia were chosen as the preferred optical materials for fabrication of the temperature sensor probe assembly.

The sensor instrumentation will be designed for continuous operation in an actual coal gasification facility under high temperatures and extremely corrosive conditions. The field test will be run for multiple months to be able to reliably demonstrate the capability of the operation in the extremely harsh gasification environment. Future field tests and evaluations of the sensing system will be the following:

**Task 1.** Installation of the sensor probe head components into gasification unit – a "dummy" probe will be installed in the gasification unit to determine performance of the components in an operating slagging gasifier.

**Task 2.** Site preparation and installation – the field test site will be prepared for installation of the sensor system. After all external infrastructure is installed for communication of the signal to appropriate location, the sensor probe will be installed in the gasfier.

**Task 3.** Testing and data collection – the system will be operated for several months to evaluate the performance.

**Task 4.** Data analysis - the data obtained during the field test will be analyzed to determine the performance of the temperature sensor in the gasification unit.