Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 11 (8): 1431-1435, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.1431.1435

Measurement of Air Temperature using Laser Interferometry

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Abstract: Measurement of gas temperature is very crucial in laser induced plasma (LIP) and laser material interaction (LMI). Temperature monitoring devices such as thermocouple has some limitations. The thermocouple cannot be placed at the laser-focusing region since it will induce unwanted external effect. To overcome, a non-contact method is proposed by using interferometric technique. A simple Michelson interferometric was aligned to detect the pressure and refractive index change of ambient air. The temperature gradient of air were recorded and analyzed by using a video camera and phototransistors. From the observation results, it clearly shown that the change of air temperature in one arm of the interferometer will result in the fringes shift of the interference pattern.

Key words: Temperature, laser, interferometry, plasma

INTRODUCTION

Since the discovery of wave properties of light by Thomas Young through his excellent Young's double slit experiment, many scientists had found numerous benefits from the interference phenomena (Al-Azzawi, 2007). Interference is the superposition of two or more waves from a coherence source and can be identified by the dark and bright fringes on observation screen. A slight change in optical path will result in phase change of the waves. This will affect the fringes pattern, in term of fringes shift of the interference pattern.

There are many techniques to generate the interference. Many scientists had proposed their technique such as Michelson interferometer, Mach-Zender interferometer, Talbot interferometer, Fabry-Perot interferometer, Sagnac interferometer and many more. Each of the techniques has their own strength based on the application and measurement space. Therefore, interferometry is an extremely sensitive method used to detect and measure small changes in the optical path, such as the change in pressure, density, refractive index and temperature based on the phase shift of interference pattern (Shakher and Nirala, 1999).

From a lot of the methods, Michelson interferometer is one of the simplest setup to form interference pattern. In Michelson interferometer, splitting light beam from a light source into two paths produces the interference. The split light is reflected by mirrors, recombine again and superpose forming interference fringes. By disturbing the optical path at one arm of the interferometer, the phase is changed causing in fringes shift of the interference (Bat'kovich *et al.*, 1999).

In pulsed laser-induced plasma (Fig. 1), the properties of plasma generated at the focusing region is very crucial. This property such as the plasma density, refractive index, intensity and temperature determines the quality of the plasma induced. One of the important properties is the temperature gradient of the plasma at the focal region. Since the laser beam is focused onto a very small region (less than 0.50 mm^2), it is not easy to detect and measure the temperature (Ali and Bidin, 2004). In fact, the plasma formation process occurs in a very short time, less than 10 ns (Ali and Bidin, 2003). Therefore, an ordinary temperature measuring device such as thermocouple is not suitable to measure such a very high-speed phenomenon and at a very small region.

Besides the laser-induced plasma, another practical application of laser is the laser material interaction as shown in Fig. 2. Plasma plume generation during the laser material interaction is very important to determine the material's surface quality. When laser beam irradiates a material's surface, the electrons are accelerated in the electromagnetic field of laser light. The electrons collide with ions; consequently the energy of the photons of laser light is transferred to the plasma. This is called inverse Bremsstrahlung. This is the dominant absorption mechanism for pulsed laser deposition. Ionization can occur when the kinetic energy of an electron colliding

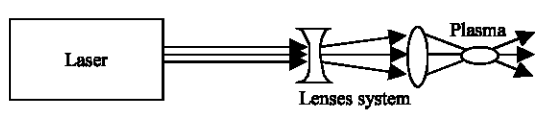

Fig. 1: Laser induced plasma

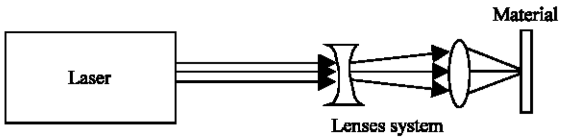

Fig. 2: Laser interaction with material

with an ion exceeds the Coulomb energy needed for that ion to bind an electron (Zheng *et al*., 2008).

It has been pointed out that temperature measurement of plasma by means of a thermocouple causes problems. This is due to insufficient contact of thermocouple with the material at the focal region (Takaki *et al*., 2001). Usually, the material's temperature measurement is achieved using a thermocouple, either in contact with the substrate holder, or carefully positioned in a blackbody enclosure situated behind the holder. However, this method suffers from the unavoidable presence of considerable temperature gradients in the material's holder. These gradients may cause differences as large as 50 to 100°C between the real materials's temperature and the thermocouple (Sitter *et al*., 1995).

In order to overcome these problems, a non-contact method is proposed. A laser beam in one arm of interferometer is placed at the focal region. When the beam is disturbed by the change of air composition, the fringes are shifted away from the center axis. In this preliminary study, such a temperature gradient of air at one arm of interferometer is measure by means of measuring the shifts of interference fringes.

MEASUREMENT PRINCIPLE

Interference is the superposition of two or more coherence waves. When two coherence waves, as example a laser light interfere to each other, a series of interference fringes will formed as shown in Fig. 3. This phenomenon can be observed at a screen, recorded by a camera and also detected by using photo detector placed at the interference fringes.

One way to producing interference is by using Michelson Interferometer method. When a coherence laser beam strikes a beamsplitter, it splits into two beams. The first beams (reference beam) are reflected by a still mirror whereas the second beam (test beam) is reflected by a moveable mirror. The beams then recombined before forming interference pattern. Interference fringes can be observed at the intersection of two beams, that is the reference and the test beam. The air condition at the first arm of the interferometer where the reference beam passes is kept constant and air condition at the second arm is disturbed. The test beam then recombined with the reference beam thus forming interference. The temperature gradient of the air at the second arm can be obtained by measuring the fringes shift of the interference pattern. The temperature can be determined from the equation of state and the relation between refractive index, density and air pressure (Hamamoto *et al*., 1989).

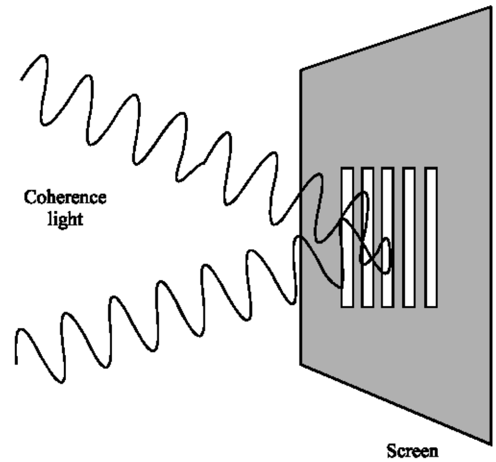

Fig. 3: Interference of two coherence waves

When the air at the second arm is heated, the refractive index changed from initial value, n_i to the value n. The change of the optical path lengths, ΔL is written as:

$$\Delta L = (n - n_i)l \tag{1}$$

where, l is the length of the disturbed air. When the beam path is changes by one wavelength, λ, there is one fringe shift on the detector. The relation between ΔL and the number of the interference fringes shift, N, is expressed as:

$$N = \frac{\Delta L}{\lambda} = (n - n_i)\frac{l}{\lambda} \tag{2}$$

When the refractive index, n is decreases, the value of N becomes negative. The relation between the refractive index and density, ρ is expressed by:

$$n^2 = \frac{1 + \frac{2\rho R_L}{M}}{1 - \frac{\rho R_L}{M}} \tag{3}$$

where, M denotes molecular mass and R_L is molecular refractivity (m^3/mol). For dilute gas, the Gladstone-Dale equation can be used, then the refractive index becomes:

$$n = 1 + \frac{3\rho R_L}{2M} = 1 + \frac{\rho R_G}{M} \tag{4}$$

where, R_G is the Gladstone-Dale molecular refractivity.

The values of R_L and R_G are constants. In ideal gas, the refractive index is expressed as:

$$n = 1 + \frac{PR_G}{R_0T} \quad (5)$$

By combining Eq. 2 and 5, the temperature is obtained as:

$$T = \frac{PR_GT_id}{N\lambda R_0T_i + R_GP_id} \quad (6)$$

where, R_0 is the general gas constant, T_i is the initial air temperature in Kelvin, P and P_i is the final pressure and initial pressure respectively.

Experimental setup: Figure 4 shows the schematic diagram of the optical system of Michelson interferometer. He-Ne laser with wavelength of 633 nm and 1 mW power was used as a light source. The beam was reflected and steered by a steering mirror and then strike a beamsplitter. The beamsplitter transmit 50% of the beam (reference beam) to the still mirror and reflect the rest (disturbed beam) to the adjustable mirror. The air at one arm is heated by a heating element up to 593 K. As a comparison, a calibrated type-K thermocouple interfaced to microcomputer was placed at the arm. The interference formation was recorded by a video camera. A light detector was placed at the interference fringes to detect the fringes shift.

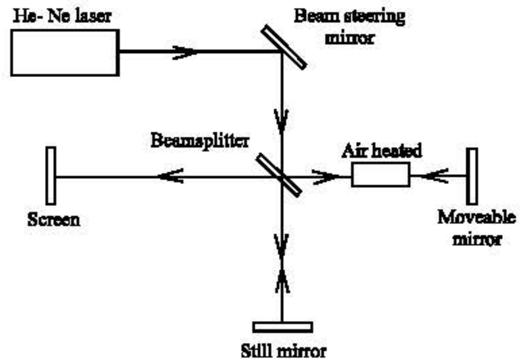

Fig. 4: Detecting air temperature at one arm of a Michelson interferometer

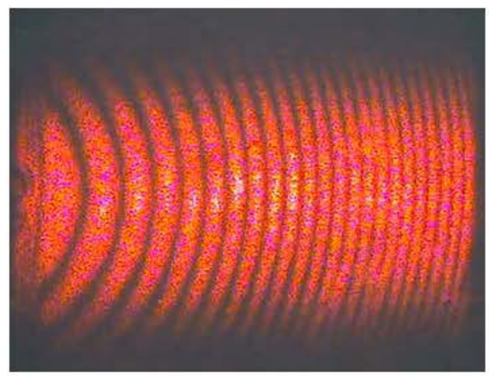

Fig. 5: Interference pattern when the lights from two arm of the interferometer are combined

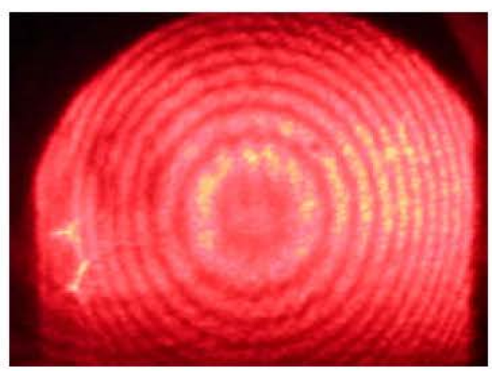

Fig. 6: Ring shape of interference pattern

RESULTS

A heating element was positioned at the second arm of the interferometer. Then it was heated from 293 K up to 593 K, with temperature difference, ΔT approximately 300 K. When the air was heated, the air molecules gain thermal energy. Consequently they start to move freely with more energetic, called kinetic energy K_E and with increasing speed. These movements cause the density of air at the heated region decreasing, but the pressure was increasing. As a result the refractive index was also decreasing. So the light beam on the arm was disturbed by the changing properties of air. The changing of refractive index causing the optical path and phase difference changed. Therefore the interference fringes were shifted.

When the lights from two arm of the interferometer are combined, series of bright and dark fringes were observed as shown in Fig. 5. The fringes are almost parallel. These parallel fringes were obtained by carefully and slowly adjusting the distance of the second arm (where the air is heated) from the beamsplitter. This procedure was performed in order to get a clear picture of the fringes pattern. In addition a set of lenses were positioned at the output of the recombined beam to enlarge the fringes pattern. Thus the fringes shifts are much easier to recorded and detected, as compared to the smaller and ring shape of interference fringes (Fig. 6).

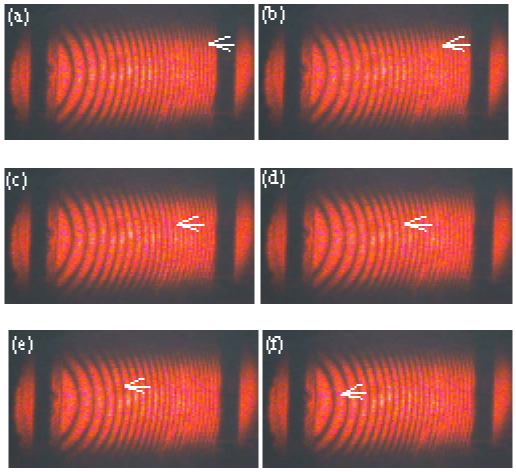

Fig. 7: Plasma expansion detected at one arm of the interferometer; (a) 0.04s, (b) 0.08s, (c) 0.12s, (d) 0.16s, (e) 0.20s and 0.24s

Then simple tests were conducted to detect laser plasma properties, especially the plasma formation and temperature at the focal region. Laser beam from the Nd:YAG laser was focused by a 62.9 mm biconvex lens into the second arm of the interferometer. Plasma was generated at the focal region thus affecting the optical path of the HeNe laser beam. Consequently the plasma formation was observed from the changes of the interference pattern. The plasma expansions were shown in fig. 7 from the initial formation at time 0.04 s until 0.24 s.

ANALYSIS AND DISCUSSION

From the observation result, it was clearly shown that the interference fringes were produce from the superposition of two lights. When the path of one light is disturbed by changing the temperature of the air then the fringes will move depending upon the light path differences. The number of fringes shifts, N was recorded and detected for analysis purposes. Some parameter such as refractive index, air density and pressure were taken for consideration in determining the temperature gradient of the air.

Instead of using a video camera to record the interference fringes shifting, phototransistor were also used to detect the number of fringes shift. By maintaining the volume of air in the vessel, the pressure, refractive index and the temperature of air in the vessel was increased when the vessel was heated. When the vessel is heated, the air molecules gain energy thus increasing the velocity. Collisions between air molecules and vessel wall increases, therefore the pressure in the vessel was increasing as well. In addition, the refractive index of the air also changes as well. Laser light that propagates through the changing refractive index of air in the vessel affects the interference pattern. The changing in the interference pattern was observed by the fringes shift on the screen.

In this study, the aim is to detect the air temperature using interferometric technique. This system is hope can detect the plasma properties such as its temperature at the focal region. Since the plasma is the fourth state of matter; the state that is containing energetic and hot ions; characterizing plasma properties can lead to many beneficial applications. The plasma under test was generated using ND: YAG laser with pulse duration of 8 ns. The peak power could reach up to 10^{-7} W and intensity of 10^{-10} W/cm^2. This very high-speed phenomenon and yet very high power and high intensity could generate a very high density and high temperature of plasma. Since the plasma formation was occur in very short time duration, detecting the plasma temperature are quite complicated. But by using the interferometric technique, the plasma formation as well its temperature can be detected. It is shown in preliminary studies as in Fig. 7 that the plasma formation causing the interference fringes shifted. In further studies the researcher hope the plasma can be measured accurately by using the interferometric technique.

But during the experiment, there are some conditions that need to take into consideration. Since the interference is very sensitive to any disturbance, so the optical components were aligned and mounted on a very rigid optical table. The optical itself is isolated from vibration from ground by using vibration isolation unit. In addition the interference is also easily shifted when there are a wind blowing. To overcome the devices such as air conditioning and fan is shut down.

CONCLUSION

It was clearly shown that the non-contact and non-intrusive measurement in air temperature measurement was made successfully by the Michelson laser interferometer. When air pressure, refractive index, density and temperature were varied, the interference fringes were shifted. The temperature gradient of air at the interferometer arm was found in a good agreement with the thermocouple. This interferometry method can be used to measure the temperature of plasma induced by pulsed laser as well the surface temperature at the laser material interaction. Extra caution should be taken into consideration during the measurement from the effects of vibration.

ACKNOWLEDGMENTS

The author would like to express thank to the government of Malaysia, Centre for Research and Innovation (PPI) and Faculty of Science, Arts and Heritage, Universiti Tun Hussein Onn Malaysia through short term project vote 0612 for the financial support in this project.

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