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Real Time Temperature Distribution Measurement of a Microheater by Using Off-Axis Digital Holography

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We describe a single shot off-axis digital holography based on a Mach-Zehnder interferometic scheme for measuring temperature distribution of a microheater. The proposed scheme has the capability of reconstructing object phase image which is dependent of the temperature distribution in real time. Experimental results shows that there is a moderate linear relationship between the measured phase and temperature in the range of 20°C to 60°C. We expect that the proposed system can provide a very reliable and fast solution in various surface temperature distribution measurement applications.

Keywords : Surface temperature distribution measurement, Single shot off-axis digital holography, Digital reference wave, Numerical reconstruction

I. Introduction

Many physical properties of materials are dependent on temperature, therefore the measurement of temperature distribution is very important. For this, various optical techniques are used widely nowadays in the field of heat and mass transfer measurement [1,2]. These methods are non-contact, non-destructive, and it can provide accurate measurement. In a group of optical methods which are called index of refraction methods, the temperature distribution is obtained by measuring the phase differences of light rays caused by variations in refractive index. In several relatively recent publications, such methods include classical interferometry [3] and holographic interferometry [4-7].

In conventional holographic interferometry, the reconstructed phase is usually calculated from three or more phase-shifted interferograms by a phase shifting technique. But, this technique requires additional experimental efforts [8]. Nowadays, with the invention of high speed microprocessors and high speed CCD cameras, digital holography has become feasible, and the digitized holographic data are processed numerically to reconstruct the images using computer programs [9-13]. Goodman and Lawrence [9] and Kronrod [14] were the first to use a computer for reconstructing a hologram. The zero-order diffraction and the two conjugate images overlap, in the in-line configuration. In classical holography, the influence of the conjugate image was overcome by the off-axis geometry invented by Leith and Upatnieks [15]. In digital holography, the recorded intensity distribution of the hologram is multiplied by the reference wave field in the hologram plane and the diffracted field in the image phase is determined by

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Fresnel integral.

In this paper, a single shot off-axis digital holography by using a Mach-Zehnder interferometer was used to investigate a temperature distribution of a microheater. Five off-axis digital holograms of a microheater object at 20, 30, 40, 50, and 60°C were captured by using a CCD camera. The digital holograms of the microheater object were processed using Matlab codes for getting a reconstructed object wave (amplitude and phase). The digital reference wave in the reconstruction algorithm should match as close as possible to the experimental reference wave. This was done in this paper by selecting the appropriate values of the two components of the wave vector k_x= 0.0097888 mm^{-1}, k_y=0.0131999 mm^{-1}. The reconstructed object phase maps at different temperatures were analyzed for various points. The experimental results showed that there is a linear relationship between phase and temperature.

II. Experimental method

1. Optical system

The holograms for each temperature were recorded using an optical setup of the single shot off-axis digital holographic system which is based on a Mach-Zehnder interferometer. The schematic diagram of the optical setup and its photo are shown in Fig. 1.

A polarized light from a diode laser with the wavelength of 635 nm was collimated by a collimating lens. Three neutral density filters were used to adjust the object and the reference intensities. Shear interferometer was used to make a reference wave that can be regarded as a perfect plane wave. The object was placed at a distance d_0=320 mm from the CCD camera of 1,024×1,024 pixels with pixel size Δx=Δy=6.4 μm.

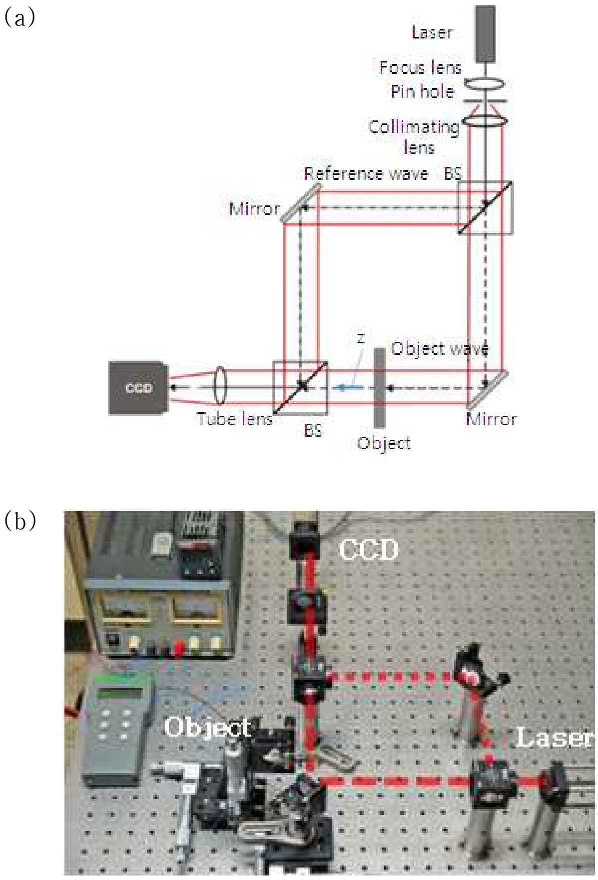


Figure 1. The schematic diagram (a) of the optical setup and (b) its photo.

2. Numerical reconstruction

In digital holography, both the amplitude and the phase of a wavefront can be recorded, i.e. phase differences can be calculated directly from holograms. When an object is illuminated by a coherence light source, the scattered light has informations about the object profile. The recording process is based on the use of two waves interferometer. Light with sufficient coherence length is split into two waves by a beam splitter. One wave, the object wave O reflected from the object interferes with the other wave, called the reference wave R, and the structure of the interference fringes pattern is correlated to the difference of optical path between the two waves.

The off-axis hologram recording and reconstruction principle is shown in Fig. 2 [16].

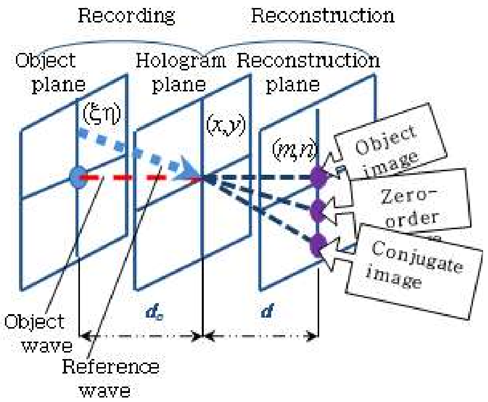


Figure 2. Recording and reconstruction diagram of off-axis digital holography.

The resulting hologram is recorded by a CCD camera and mathematically described by the following expression:

$$I_H(k,l)=|O|^2+|R|^2+R^*O+RO^* \qquad (1)$$

Here, $R*$ and $O*$ denote the complex conjugate of the reference wave and the object wave, respectively. We obtain the reconstructed wave front $\psi(m,n)$ in the reconstruction plane by computing the discrete Fresnel integral of the digitized hologram $I_H(k,l)$ in the hologram plane $0xy$.

$$\psi(m,n)=\frac{\exp\left(\frac{i2\pi d}{\lambda}\right)}{id\lambda}exp\left[\frac{i\pi}{\lambda d}(m^2\Delta\xi^2+n^2\Delta\eta^2)\right] \qquad (2)$$
$$\times F\left\{R_D(k,l)I_H(k,l)\exp\left[\frac{i\pi}{\lambda d}(k^2\Delta x^2+l^2\Delta y^2)\right]\right\}$$

Here, k,l,m,n are integers. d and λ are the distance between the reconstruction plane and hologram plane, and the wavelength of the laser source, respectively. F denotes the 2-D fast Fourier transformation. Δx and Δy define the sampling intervals in the hologram plane. The sampling intervals $\Delta\xi$ and $\Delta\eta$ in the reconstruction plane are related to the size of the CCD (L) and to the distance d by the following relation.

$$\Delta\xi=\Delta\eta=\lambda d/L \qquad (3)$$

The reconstructed wave front is an array of complex numbers. An amplitude-contrast image and a phase-contrast image can be obtained by using the following intensity $[Re(\psi)^2+Im(\psi)^2]$ and the argument *arctan* $\{Re(\psi)/Im(\psi)\}$, respectively. $R_D(k,l)$ is a computed replica of the reference wave called a *digital reference wave*. If we assume that a perfect plane wave is used as reference for hologram recording, R_D can be calculated as follows:

$$R_D(k,l)=A_R\exp\left[i(2\pi/\lambda)(k_xk\Delta x+k_yl\Delta y)\right] \qquad (4)$$

where, A_R is the amplitude and k_x and k_y are the two components of the wave vector that must be adjusted such that the propagation direction of R_D matches as closely as possible with that of the experimental reference wave. By using this digital reference wave concept, we can obtain an object wave which is reconstructed in the central region of the reconstruction plane.

3. Temperature distribution measurement

In order to evaluate the real temperature field of an area of the microheater, the surface temperature of the microheater was measured by using a T type thermocouple probe and was compared with calculated results based on the proposed off-axis digital holographic system.

The holograms we got as we varied the temperature of the object (microheater) were processed and analyzed by using codes written in Matlab. The whole numerical reconstruction and temperature computation process is given by the flow chart shown in Fig. 3. The absolute phase values at a selected point of the two states (without heating and with heating) of the microheater surface were determined from reconstructed phase maps.

The phase difference provides information on the

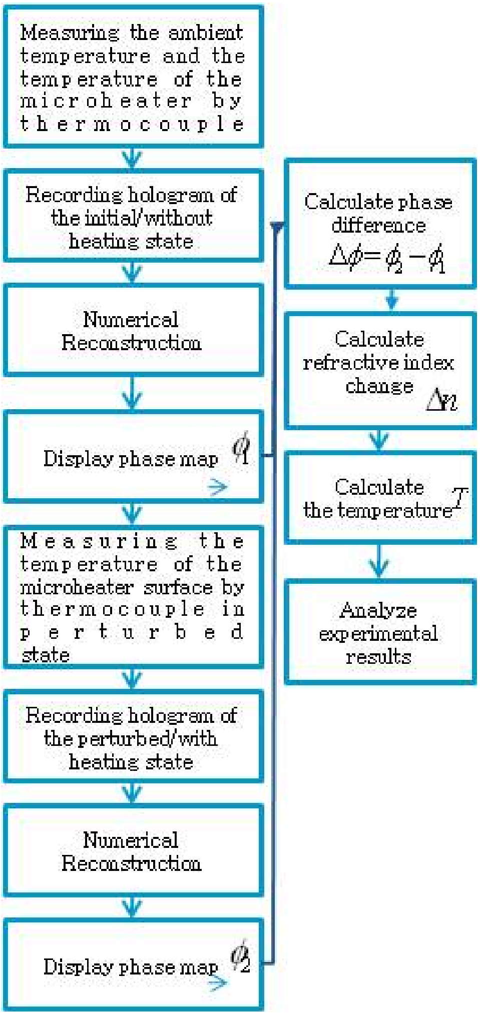


Figure 3. Flow chart of numerical reconstruction and temperature calculation process.

microheater between the two states. This phase difference acquired by a light propagating in the z direction (see Fig. 1) is proportional to the optical path length change according to

$$\triangle\phi = \frac{2\pi l}{\lambda}\Delta n \tag{5}$$

where, l is the thickness of the substrate of the microheater. For our system, $l = 1$mm.

The change in phase is related to the thermo-optic coefficient of the material. This is due to the change in the refractive index of the material caused by the change in temperature.

$$\triangle n = \frac{dn}{dT}\triangle T \tag{6}$$

Here, $\triangle n$ and dn/dT are the refractive index change and the thermo-optic coefficient of the material, respectively. The change in the refractive index of the material [17] (in this case, substrate of the microheater) was calculated from the Eq. (5). The thermo-optic coefficient used in this study was $dn/dT=(1.55\pm0.05)\times 10^{-5\,o}C^{-1}$.

From Eq. (5) and (6), the temperature of the microheater surface can be calculated as follows:

$$T=\left(\frac{\Delta\phi\lambda}{2\pi l}/\frac{dn}{dT}\right)+T_o \tag{7}$$

where, T_o is the ambient temperature measured by a thermocouple probe.

III. Results and discussion

Fig. 4 shows the whole numerical reconstruction process which uses a single shot off-axis hologram of the microheater object. As depicted in Fig. 4(a) through 4(d), 2D-FFTs was implemented for using the spatial filtering approach. The inverse 2D-FFT after filtering out the undesired two terms, the complex object wave O depicted in Fig. 4(d) and 4(e) in the hologram plane $0xy$ were extracted. After the spatial filtering step, the object wave O in the hologram plane was multiplied by the digital reference wave R_D. The final reconstructed wave front $\psi(m,n)$ in the reconstruction plane by using the discrete Fresnel transform as demonstrated in Fig. 4(g) and 4(h) was recorded. Fig. 5 shows the reconstructed object phase maps at different temperatures, 20, 30, 40, 50 and 60°C, respectively. A median filter was used to reduce the noise of the reconstructed phase maps. The phase at each different temperature was extracted at a selected pixel point (644,463) from the 800×800 full pixel image.

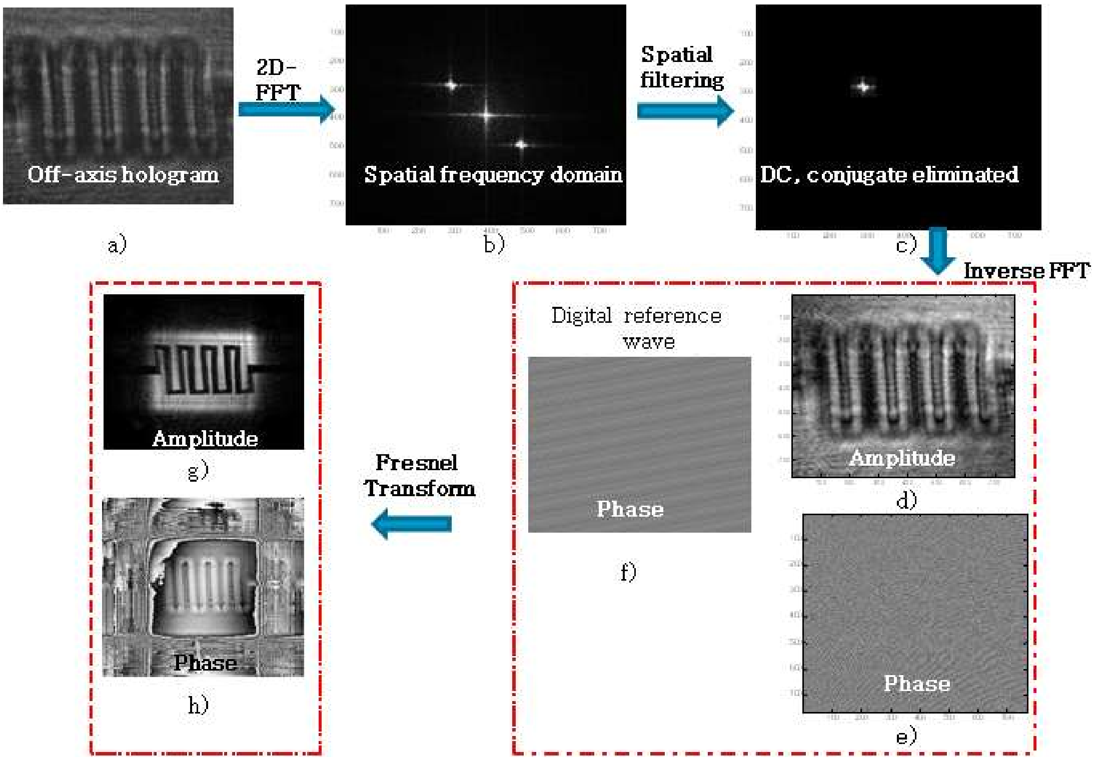
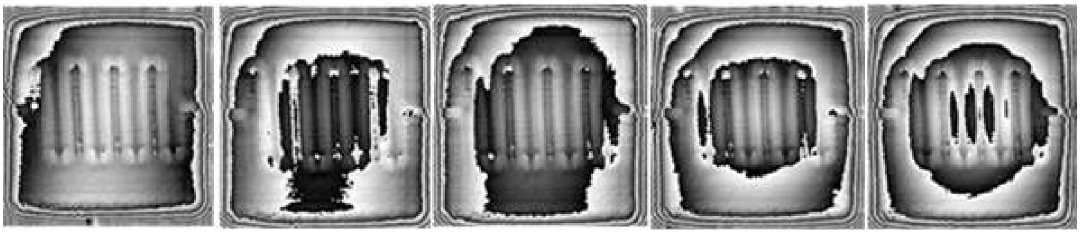


Figure 4. Reconstruction steps of the conventional spatial filtering based phase contrast off- axis digital holography: (a) Off-axis holography, (b) Fourier transformed spatial frequency domain data, (c) Spatially filtered data, (d), (e) Inversely Fourier transformed data, (f) Phase map of the digital reference wave, (g), (h) Reconstructed object wave (amplitude and phase).



(a) (b) (c) (d) (e)

Figure 5. Reconstructed object phase maps obtained by varying the microheater temperature: (a) 20°C, (b) 30°C, (c) 40°C, (d) 50°C and (e) 60°C.

The relationship between the extracted phase and temperature is shown in Fig. 6. It is found in Fig. 6 that there is a linear correlation between temperature and phase by the equation of $T=6.800\phi+22.211$. As can be seen in Fig. 5, we can say that the proposed temperature distribution measurement technique can provide a real time temperature map measurement capability, since we used just a single hologram for measuring the temperature map at a specific temperature.

IV. Conclusion

Real time temperature distribution of a micro-heater was measured by using a single shot off-axis digital holography. The Matlab code for getting the reconstructed object wave (amplitude and phase) which mainly includes 2D-FFT, spatial filtering, inverse 2D-FFT Fresnel transform was developed. Experimental results showed that there is a moderate linear relation-

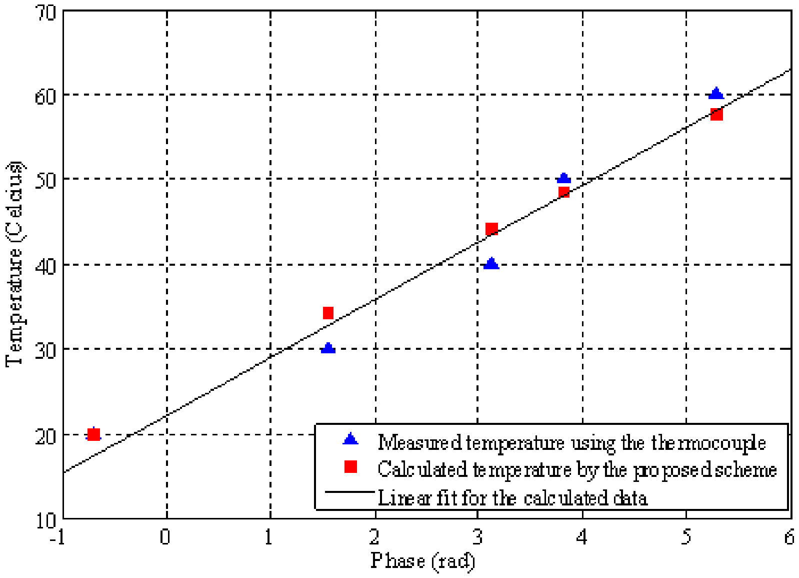


Figure 6. Relationship between temperature and phase obtained by the proposed off−axis digital holographic system.

ship between the measured phase and temperature in the range of 20°C to 60°C. We claim that the single shot off−axis digital holography can provide a very reliable and fast solution in measuring the temperature distribution of micro−fluidic systems.

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Off-Axis 디지털홀로그래피를 이용한 마이크로히터의 실시간 온도분포측정

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(2011년 2월 14일 받음, 2011년 3월 9일 수정, 2011년 3월 11일 확정)

본 논문은 마이크로히터표면의 실시간 온도분포측정을 위한 마하젠더 간섭계 기반의 off-axis 디지털홀로그래피기술에 대한 것이다. 제안된 방법은 재료표면의 온도분포에 직접적인 함수인 2차원 위상 분포를 측정하고, 이를 통해 실시간으로 재료표면의 온도 map을 측정할 수 있다. 본 논문에서는 섭씨 20도에서 60도 사이의 온도구간에서 마이크로히터 표면의 위상변화와 실제표면온도가 선형적인 관계가 있음을 실험적으로 보였다. 제안된 방법은 재료표면의 온도분포를 실시간으로 측정하고자 하는 다양한 응용분야에 적용될 수 있을 것으로 기대된다.

주제어 : 표면온도분포특정, 단일측정 off-axis 디지털홀로그래피, 디지털 기준파면, 수치적 복원

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