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Numerical reconstruction of an infrared wavefront utilizing an optical phase modulation device

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Abstract

We utilize nitroanisole, that absorbs infrared (IR) radiation as heat, as an optical modulation device based on a thermal process. The nitroanisole exhibits a thermal lens effect, i.e. a temperature dependent refractive index. Hence, the nitroanisole can induce phase modulation to visible light, in direct response to intensity of the incident IR radiation. The proposed method can be used to obtain the phase modulation distribution that corresponds to the IR intensity distribution, i.e. the IR hologram itself, on the nitroanisole by examining the phase map of visible light that is modulated upon passing through the nitroanisole. The IR wavefront can be reconstructed by calculating extracted IR holograms through the Fresnel transform. It is verified that both the amplitude and the phase of the IR wavefront can be reconstructed accurately by proposed method.

Keywords: Digital holography; Infrared holography; Nitroanisole; Phase modulation

1. Introduction

With the development of the high resolution charge-coupled device (CCD), digital holography techniques [1–3] that uses a CCD as a holographic recording medium may now be applied practically for 3D-image reconstruction, surface profile measurement, etc. This technique is able to attain high accuracy by combining phase shifting methods. A visible light source is mainly used for digital holography since conventional CCDs are designed to be sensitive to visible light. If this technique can be used in middle and far infrared (IR) regions in the same way, its breadth of applications can be expanded to various fields, such as analysis of large defects or deformations, medical diagnosis, non-destructive inspection, etc. Regarding for holographic recording media for use in the IR spectrum region, detectors, such as pyroelectric devices, HgCdTe diodes, etc., which are sensitive to IR radiation can record the IR holograms [4]. On the other hand, the use of some holographic recording materials based on a thermal process at the wavelength of 10.6 μm has been also studied [5–8]. Although the time resolution or the sensitivity of such materials is lower than that of opto-electric detectors, they have sufficiently spatial resolution to record the IR holograms. An IR wavefront can be reconstructed easily with illuminating these materials (IR holograms) by a visible laser. However phase maps of the IR wavefront are not obtained in this method since only intensity distribution of reconstructed images is observed.

In order to reconstruct not only amplitude but also phase of the IR wavefront, we propose a method to digitally extract IR holograms by utilizing nitroanisole based on a thermal process as an optical phase modulation device. The nitroanisole exhibits a thermal lens effect [9–12], i.e. a temperature dependent refractive index, and it absorbs IR radiation as heat. Hence, the nitroanisole can induce phase modulation to visible light, in direct response to intensity of the incident IR radiation. The IR hologram, which are created by an IR reference wave and an IR object wave on the nitroanisole, function as a

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phase hologram for visible light. The proposed method can be used to obtain the IR hologram as the phase modulation distribution that corresponds to the IR intensity distribution on the nitroanisole by examining the phase map of visible light that is modulated upon passing through the nitroanisole. Once the IR hologram is extracted, we can reconstruct the intensity field and the phase map of the IR object wave by numerical calculation based on the Fresnel transform. In addition, IR holograms can be stored with sufficient detail since a high-resolution CCD that is sensitive to visible light is applied for recording the information of the IR holograms.

The aim of our work is to demonstrate experimentally the digital reconstruction of the IR holograms which are constructed on the nitroanisole. We first describe the procedure to obtain the phase modulation distribution, which function as a phase hologram for visible light, made by interference of IR beams on the nitroanisole. Then, we present the experimental results. The results show that both the amplitude and the phase of the IR wavefront can be reconstructed accurately.

2. Nitroanisole as an optical phase modulation device

The nitroanisole has three chemical arrangements, namely *o*-, *m*-, and *p*-variants. We propose to use *o*-nitroanisole which is a colorless to slightly yellow liquid with a boiling point of 277 °C, a melting point of 9.4 °C, and molecular weight of 153.14, as the optical phase modulation device. The nitroanisole has a large thermal lens effect, i.e. a strong temperature dependence on the refractive index. We tested to verify that the refractive index of the nitroanisole varied with temperature at a rate of -1.1×10^{-3} [$1/T$]. In addition, we confirmed that the nitroanisole absorbs approximately 50% of incident IR laser irradiation of wavelength 10.6 μm in case of that its thickness was 10 μm and irradiation density was 2.0 W/cm^2. Therefore when the nitroanisole is irradiated by the IR laser, the temperature rises and the refractive index decreases. This effect causes phase modulation to visible light, in direct response to intensity of the incident IR laser on the nitroanisole. In case of that the IR holograms are created on the nitroanisole, the nitroanisole functions as a phase hologram for visible light. The IR holograms are created transiently while the nitroanisole is irradiated by the IR laser. Hence, the IR holograms will vanish instantly when the IR irradiation is stopped.

We established in previous research [13] that the nitroanisole has a spatial resolution of at least 8 lp/mm, based on measurements of the diffraction efficiency dependent on the spatial frequency of the IR interference fringe. Therefore, it is expected that the nitroanisole has high spatial resolution compared with conventional IR cameras. Also, it would be easy to make a larger two-dimensional nitroanisole device that does not require a matrix structure, by filling the space between two substrates with nitroanisole. Thus, the proposed nitroanisole device is much simpler and easy to handle compared with existing IR sensitive detectors that require a cryogenic system or matrix structure, etc.

In our method the converter material has to give the phase modulation to the probe laser with respect to the IR irradiation. In addition, the IR hologram have to be created transiently in order to obtain the IR hologram with utilizing the phase shifting method. Hence, the nitroanisole is one of the suitable material that satisfies these requirements.

3. Extraction procedure of the IR holograms

In this section, we describe the procedure for extraction of the phase modulation distribution, namely the IR hologram, that the nitroanisole imparts to incident visible light, in direct response to the irradiation of the IR beams. The optical setup under consideration is shown in Fig. 1. It consists of two holographic recording setups. The first one is an off-axis holography setup in which the light source is an IR laser, and this one is used for creating an IR hologram, that subsequently may be reconstructed, on the nitroanisole. The other one is a digital holography setup based on a Mach–Zehnder interferometer in which the light source is a visible laser, and this one records the visible interference pattern modulated by passing through the nitroanisole on which the IR hologram is created, by utilizing the phase shifting method. By rotating a parallel plate, which was fabricated with accuracy of $\lambda/10$, determinate phase shift required for use in the phase shifting method is given. We applied a general four step algorithm with $\pi/2$ shift between each of four frames in order to derive an accurate phase map of the visible interference pattern registered by the CCD Fig. 2.

Let us now consider the intensity distribution of the interferogram constructed by the IR object and referece wave at the nitroanisole. Supposing that the optical complex amplitude of the IR object wave and the IR reference plane wave on the nitroanisole plane ξ–η are denoted respectively by $\mathbf{O}_{\mathrm{IR}}(\xi,\eta)$ and $\mathbf{R}_{\mathrm{IR}}(\xi,\eta)$, we can describe the intensity distribution of the IR hologram on the nitroanisole as

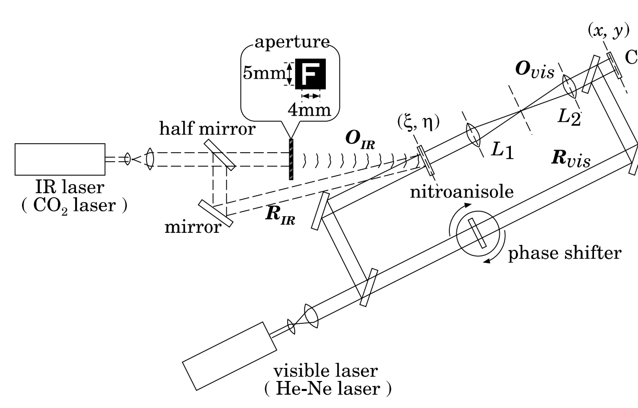

Fig. 1. The optical setup for the extraction of the IR hologram.