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Full Length Article

Three-dimensional hologram printing by single beam femtosecond laser direct writing

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ABSTRACT

This article demonstrates three-dimensional (3D) hologram printing in polymethyl methacrylate (PMMA) and linthum niobate ($LiNbO_3$) samples by means of single beam femtosecond laser direct writing technique. We have printed double-layer 3D hologram, having a background and foreground layer, inside PMMA substrate. Triple-layer 3D hologram, comprising a background, middle, and foreground layer, has been fabricated inside LiNbO3 sample. In both cases, each layer is superimposed over the bottom layers of the holograms. The 3D holograms consist of images (in our case, letters) printed in multiple layers so that each layer is alternately visible depending upon the angle of perspective of the observer. Initially, the target image is converted to an equivalent image by a set of periodic micro-metric lines. Afterwards, using femtosecond laser irradiation a set of periodic diffraction gratings have been fabricated in lieu of micro-lines to form the images in multiple layers, where the orientation of the diffraction gratings is different in different layers. As a result, the 3D holograms display a distinctive multi-color effect.

1. Introduction

Typically, the term "hologram" refers to photographic recording of a light field that is used to display a 3D image of the holographed object. After the initial invention and development of fundamental concepts of holographic method by Denis Gabor in 1948, the holographic techniques come to the forefront of the research field [1]. However, it was necessary to wait more than a decade until the discovery of the functional laser source to enable the development of first practical optical holograms capable of recording 3D objects in 1962 [2,3]. The conventional hologram recorders necessitate a coherent radiation source (usually a laser source) to form interference pattern through the interference between the object wave and reference wave, generated from the same light source, which interference pattern is recordable as a hologram [4]. Because of variation in properties, holograms can be classified in many ways. The following eight fundamental classes can be commonly used for classifying holograms: (i) transmission/reflection mode holograms, (ii) thick/thin holograms, (iii) volume/plane holograms, (iv) color/monochrome holograms, (v) optical/microwave/acoustic/seismic/computer holograms, (vi) amplitude/phase holograms, (vii) time-average/single- or double-exposure holograms, and (viii) sideband/inline holograms [5,6]. The conventional holograms are recorded in either a transmission or reflection mode where the mode depends on the transmission property of the target material. Transmission holograms are observed by shining a laser source through the object and viewing the reconstructed image from the side of the hologram direction opposite to the source. On the contrary, the reflection holograms use white light as an illumination source where the light source and the viewers are positioned on the same side. Holograms can be printed using single or multiple exposures. The amplitude, phase, or both of them of the reconstruction beam can be altered to form different virtual or real images. Since their invention, holographic techniques proved their potential in a dynamic field of science and technology: 3D display [7], optical metrology [8], medicine [9], microsurgery [10], and security & authentication [11].

Since the discovery, femtosecond laser have been considered as a versatile tool for patterning micro-scale diffractive elements in both transparent and non-transparent materials [12–16]. Femtosecond laser holography, based on light interference concept,

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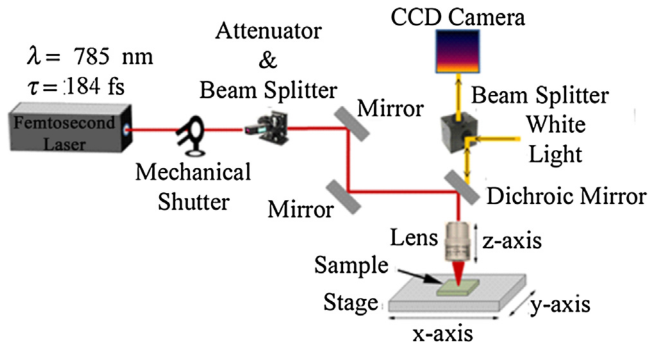

Fig. 1. Schematic diagram of the femtosecond laser system for printing 3D rainbow transmission holograms.

have attracted the researchers because of their ability to record static holograms [17,18]. The conventional way of femtosecond laser holography is to record holograms using the interference of two light beams coming from the same femtosecond laser source. In contrast, a series of research articles had been published on two-color holography, initially introduced by Buse et al. [19], where holographic gratings were recorded by light beams having considerably different frequencies [4]. Most of these holographic recorders require a complex setup requiring beam splitter, spatial light modulator, and Fourier objective system. The alternate technologies for printing holograms in solid materials include electron-beam lithography [20] and ion-beam lithography [21], which are very expensive and time consuming. Thus, it is desirable to find a simple technique for printing 3D holograms in transparent solid materials.

In this paper, we proposed a novel technique for printing 3D rainbow transmission holograms inside transparent materials by a single laser beam. Double-layer 3D hologram was printed inside PMMA sample, whereas, triple-layer 3D hologram was engraved inside $LiNbO_3$ substrate. In both cases, we imprinted images in different layers where the images were represented by different set of gratings oriented in different directions. Because of the dependence of light diffraction from the diffraction gratings on the incident and azimuthal angles of light, the image of each layer was alternately visible to the observer in different perspectives, when a white light is impinged upon the 3D holograms. The 3D rainbow transmission holograms displayed multi-color effect where the range of colors was different for various layers. Although the printed 3D holograms were constructed by English letters, any kind of images or symbols and their combinations can be considered for printing a distinctive hologram especially suitable for security and authentication.

2. Experimental details

The 3D holograms were printed using a Ti:sapphire femtosecond laser operating at the central wavelength (λ) of 785 nm that emitted ultra-short laser pulses having pulse width of 184 fs and pulse repetition rate of 1 kHz. Fig. 1 shows the schematic diagram of the femtosecond laser system. The experiments were carried out on highly transparent PMMA (refractive index (η): 1.489 at 800 nm; thickness (d): 1 mm) and $LiNbO_3$ (η: 2.255 at 800 nm; d: 500 μm) samples where the transmittance of light was greater than 90% in the visible spectrum.

We printed double-layer 3D hologram inside PMMA sample and triple-layer 3D hologram inside $LiNbO_3$ sample by irradiating a single femtosecond laser beam of variable laser fluence in multiple layers at a scanning speed of 0.05 mm/s. The power of the linearly polarized Gaussian-shape femtosecond laser beam was attenuated by a computerized attenuator consisting a rotatable quartz phase $\lambda/2$ wave plate and a polarizing beam splitter that transmitted p-polarized laser beam for printing holograms inside the samples. The samples were placed on a 3-axis linear translation stage having resolution of 100 nm in all directions. The femtosecond laser beam was focused in different layers inside the transparent samples by means of a 50 × achromatic objective lens. The irradiation conditions of the laser beam, beam location, and pattern type (e.g. image, symbol, or letter) were controlled by the main program of the laser system. To print any image in any layer, the first task was to import the desired image in the main program and convert it to an equivalent image comprising a set of periodic micro-lines (represented by diffraction gratings). The femtosecond laser was focused in the target layer and periodic gratings of appropriate orientation were fabricated to print the desired image in that layer. A white light was illuminated upon the holograms from the direction opposite to the observer under different incident/azimuthal angles suitable to observe different layers of the holograms. The samples were investigated under an optical microscope (Axioskop 40 Pol, ZEISS). The photographs of the samples were captured using a digital single-lens reflex (DSLR) camera.

3. Results and discussion

As mentioned before, we fabricated double-layer 3D hologram inside PMMA substrate and triple-layer 3D hologram inside $LiNbO_3$ samples by means of femtosecond laser direct writing. To obtain holographic effect, periodic diffraction gratings of different orientations were fabricated in different layers inside the samples.

3.1. Double-layer 3D hologram inside PMMA substrate

The double-layer 3D hologram was fabricated inside PMMA substrate in two steps. At first, we printed the target image on the background layer to avoid any damage in the foreground layer. A femtosecond laser beam of 5.6 μJ/cm^2 laser fluence was focused 30 μm inside the PMMA sample to fabricate a set of periodic horizontal gratings (orientation: 0°), representing letter "S," in the background layer. Afterwards, the laser beam was moved up by 20 μm to focus on the foreground layer (10 μm inside the PMMA sample) of the hologram. As a result, the layer gap of the hologram became 20 μm. The laser beam was irradiated to engrave a set of vertical gratings (orientation: 90°) for printing the letter "G" in the foreground layer. Fig. 2(a) depicts the formation mechanism of double-layer 3D rainbow transmission hologram in PMMA sample. After femtosecond laser irradiation, we achieved the double-layer 3D hologram of Fig. 2(b). The line width and period of the gratings of the foreground layer were 5.3 μm and 15 μm and background layer were 3.6 μm and 15 μm throughout the sample. In order to observe different layers of the double-layer hologram, white light was illuminated from the bottom side of the sample under different incident angles. The photograph of letter "G," printed on the foreground layer, is shown in Fig. 2(c) where the optical microscope (OM) image (top view) is tagged with the photograph. The photograph of letter "S," printed on the background layer, is shown in Fig. 2(d) where the OM image (top view) is tagged with the photograph. Fig. 2(e) represents the side view of the double-layer hologram imprinted PMMA sample.

3.2. Triple-layer 3D hologram inside $LiNbO_3$ substrate

For triple-layer 3D hologram inside $LiNbO_3$ substrate, we began with patterning the target image on the background layer, which was followed by patterning on the middle and foreground layers. Initially, the femtosecond laser beam of 7.8 μJ/cm^2 laser fluence was focused 50 μm inside the sample to fabricate a set of horizontal gratings (orientation: 0°), symbolizing the letter "C," in the background layer.