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# A high-resolution fringe printer for studying synthetic holograms

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## ABSTRACT

A high resolution fringe printer developed for driving the research in computer-generated holograms is presented. This fringe printer consists of a rotation drum and a laser diode and is capable of printing elliptical dots of 1.5 *times* 3.0 microns in diameter on photosensitive films. These dot sizes are approximately converted into resolutions of 17,000dpi × 8,500dpi. The horizontal and vertical angles of viewing-zone of holograms printed by the printer reach 24 and 12 degrees, respectively. The designed maximum scan speed is more than 200mm/s, and at current stage of development, a hologram of approximately 50 mm square can be printed in approximately 2 hours.

**Keywords:** Digitally synthetic hologram, Computer-generated hologram, CGH, 3-D image, Fringe printer

## 1. INTRODUCTION

Computer-generated holograms (CGH), sometimes called digitally synthetic holograms, are one of candidates for sophisticated three-dimensional digital imaging system in the future. But the CGHs at current stage are suffering from twin problems before growing into practical use. One is the problem of its computation. Generation of CGHs is, in general, much time-consuming process even in modern CPU technology.[1,2] The other is the problem of its fabrication. Resolution of printed fringe pattern of CGHs directly leads to angle of its viewing-zone. For example, a laser printer in resolution of 1,200 dpi can generate a hologram that has only an angle of viewing-zone of 1.7 degrees. If we can use micro-processing technology such as e-beam writing[3] or photo-lithography for fabricating LSI device, we can print CHGs of which viewing zone is larger than that of conventional analog holograms. However, these high-technologies are, in general, too expensive to print only a piece of 3-D picture. Furthermore, time necessary for fabricating a hologram is usually too long to fabricate experimental holograms to verify algorithm for its computation.

This printing-problem has blocked progress in computer algorithm for synthetic holograms. For example, even if someone invents an algorithm to calculate fine holograms very fast, they can not verify their idea because of no instrument to print the synthetic hologram.

To overcome this situation, i.e. lack of easy printing equipments for CGHs, some low-cost fringe printer systems have been reported. Sakamoto et al. proposed to use a specific CD-R writer available on the market as fringe printer for CGHs.[4] However, the CD-R writer they reported is not available at the present time. Yoshikawa et al. also reported a fringe printer, in which a LCD is used as SLM and images displayed on the LCD are transferred to photosensitive materials.[5,6] This is very fast printing system. The only drawback in the fringe printer is that resolution of the printed fringe pattern is determined by quality of optics for transferring images.

We also presented fringe printer system in former reports.[7,8] The fringe printer can print fringe patterns dot by dot by focusing single laser beam onto photosensitive plate, and therefore optical system is simple and inexpensive. But its printing speed was very slow. The new printer system reported in this article is an improvement on the previous one. In the new printer, the improvement is made on the mechanism for scanning the laser spot, i.e. a rotation drum is introduced into the new printer and plays an important roll to increase scan speed drastically.

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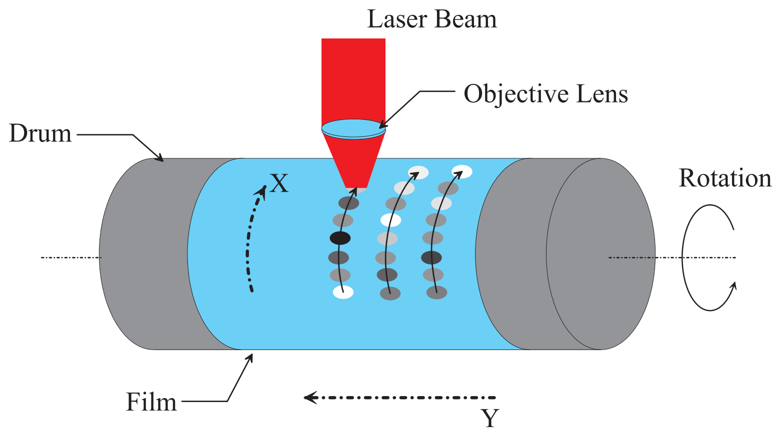


**Figure 1.** The basic structure of the fringe printer. Fringe patterns are printed dot by dot using a rotation drum.

## 2. PRINTER SYSTEM

### 2.1. Basic Structure

Mechanism of the fringe printer is shown in Fig. 1. This printer is nothing more than an extraordinary high-resolution laser printer in a sense. The fringe patterns of a hologram are formed from many small dark dots printed on photosensitive film used in recording analog holograms by focusing a laser beam. However, rotational polygon mirrors and $f-\theta$ lens system used in ordinary laser printers are not used in this printer. Instead of these complicated optomechanical mechanism, the photo-sensitive film is directly pasted on a drum and a laser beam is focused on the film by objective lens. A laser diode is used as the laser source, and its output is modulated to give different gray-level to each printed dot. Rotation of the drum provides X-scan of the laser spot, while Y-scan is given by translational movement of objective lens and laser spot along the rotation axis of the drum.

### 2.2. Optics and the rotation drum

Optics of the fringe printer is shown in Fig 2. Output of the laser diode is reflected by the surface of a glass prism to attenuate the power to one or two order of magnitude, because intensity of the focused laser spot is too strong to expose photosensitive film properly and control gray-level of printed dots. All optical instruments are installed on a base plate loaded on a pulse-motor translational stage to provide Y-scan.

The rotation drum is driven by AC servomotor and supported by a rigid and precision shaft bearing mechanism. Photographs of printer system is shown in Fig. 3

### 2.3. Control system

Fig. 4 shows the block diagram of a circuit controlling the printer. Y- and Z-stage are controlled by a PC via the stage controller connected by the serial interface. AC servomotor is also controlled by the PC via the motor driver installed in PCI bus. A build-in rotary encoder in the servomotor triggers the pulse generator, and the pulse generator generates a series of pulse corresponding to a line in X-scan. This pulse string triggers one-shot pulse generator and D/A converter installed in PCI bus. Finally, a height-controlled pulse string is generated by a C-MOS switch and fed to LD driver.

## 3. RESOLUTION AND PRECISION OF THE CONSTRUCTED PRINTER

### 3.1. The size of a dot

Dot size printed on the film gives the resolution of the printer. Fig. 5 shows the photomicrograph of a dot string printed with laser irradiation at intervals of 2 $\mu$m. Each dot has elliptical shape owing to the elliptical beam mode of the LD output and its size (diameter) measures approximately 1.5 $\mu$m in the direction of X-scan and

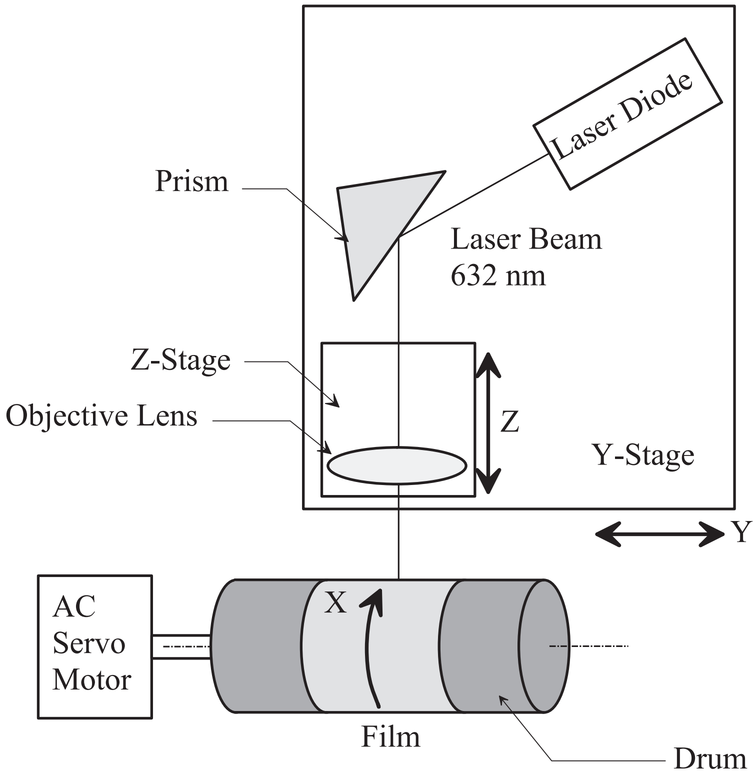


**Figure 2.** Optics of the fringe printer.

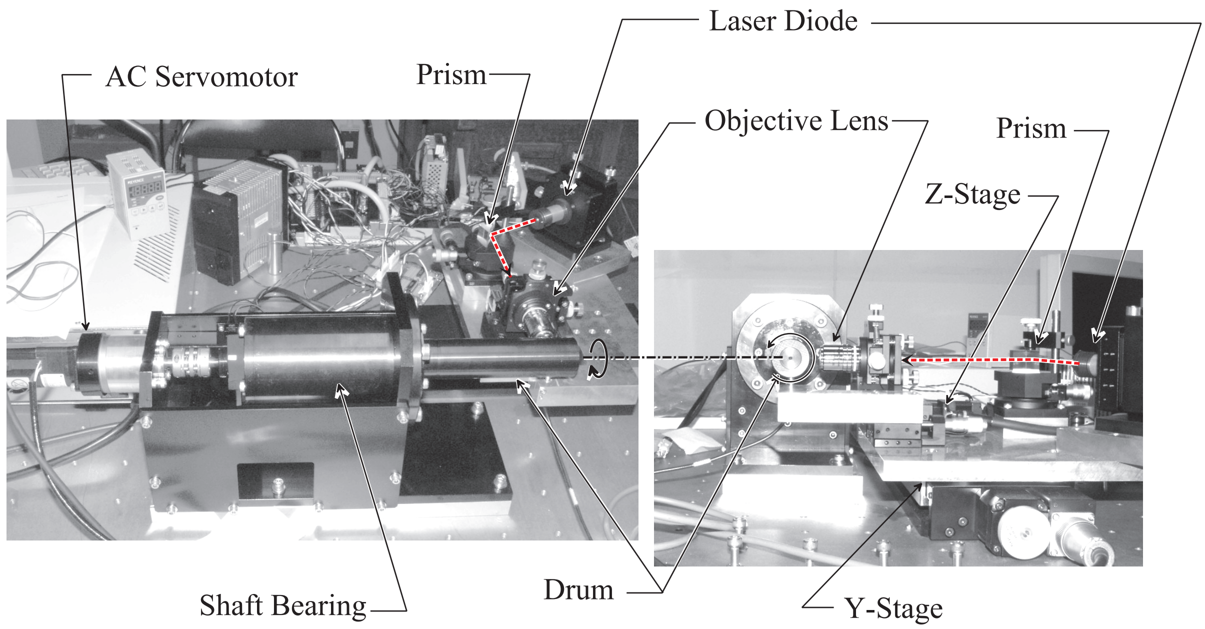


**Figure 3.** Photographs of the constructed fringe printer.

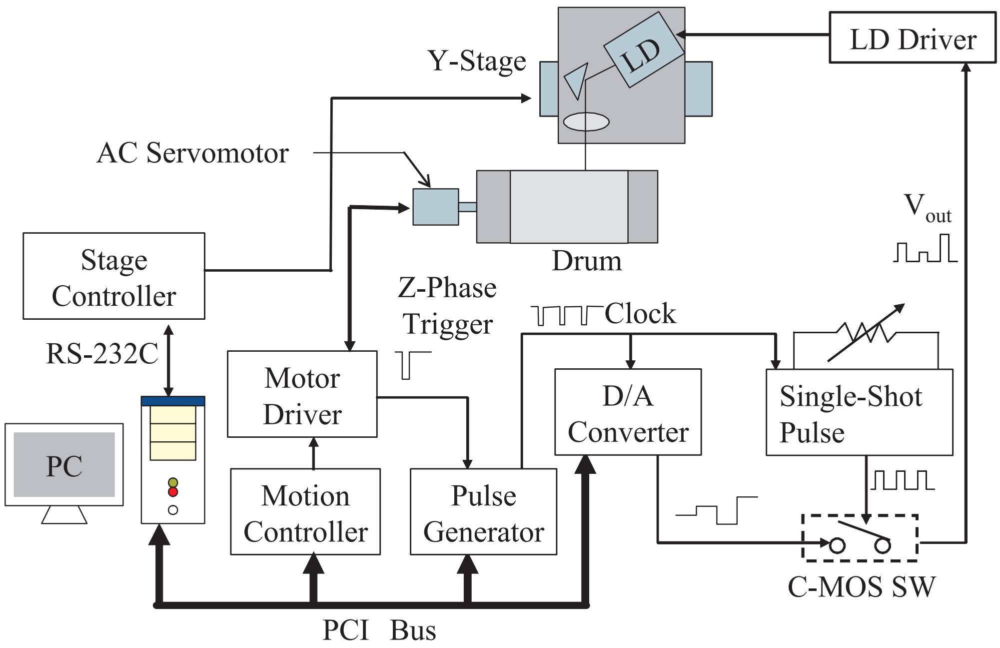


**Figure 4.** The block diagram of control system.

3.0 $\mu$m in the direction of Y-scan. As a result, the resolution of the printer is estimated to be approximately 17,000 dpi × 8,500 dpi.

### 3.2. Precision of dot positions

Precision of dot positions in the direction of Y-scan is given by that of the Y-stage, while precision in the direction of X-scan is affected by several factors such as jitter of encoder signals or unevenness of rotational speed of the AC servomotor. Fig. 6 shows the photomicrograph of some lines of printed dot string in the X direction. The interval in the X direction is 2 $\mu$m again.

Fluctuation of dot positions in X-scan is approximately 1 $\mu$m at the starting point of the scan, while it reaches approximately 5 $\mu$m at the end of the scan. The former fluctuation is attributed to jitter of the encoder signal. The latter fluctuation is larger than that of the former and most likely caused by fluctuation of the rotational speed of the servomotor.

### 3.3. Eccentricity of rotation of the drum

Any mechanism for automatic focus adjustment is not installed in this fringe printer at this stage. Therefore, eccentricity of rotation of the drum directly leads to focus error. As shown in Fig. 7, an overhung drum and precision shaft bearing designed to keep eccentricity to minimum are adopted in this printer. Values of eccentricity

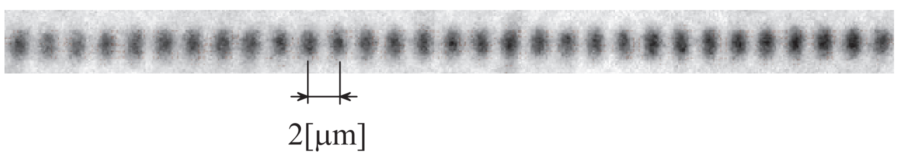


**Figure 5.** The photomicrograph of a dot string. Dots are printed at an interval of 2 $\mu$m. The speed of rotation is 2 rps (220 m/s).

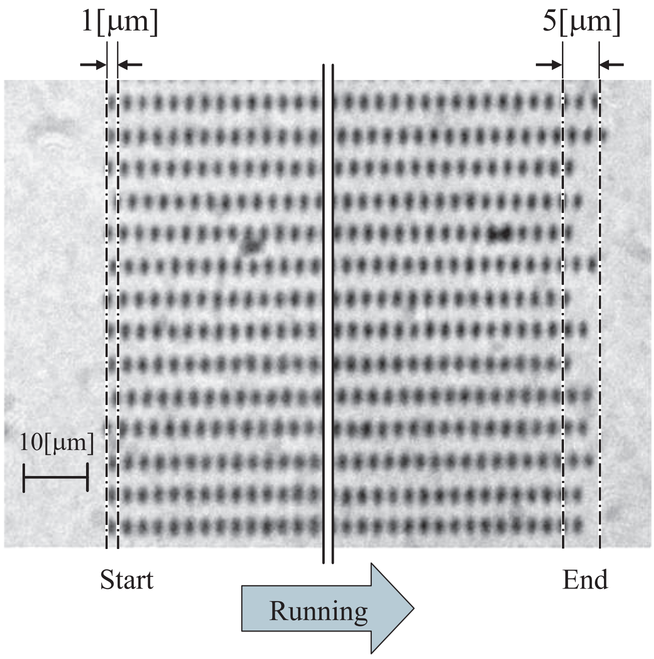


**Figure 6.** The photomicrograph of some lines of dot strings in the direction of X-scan. The speed of rotation is 2 rps (220 m/s).

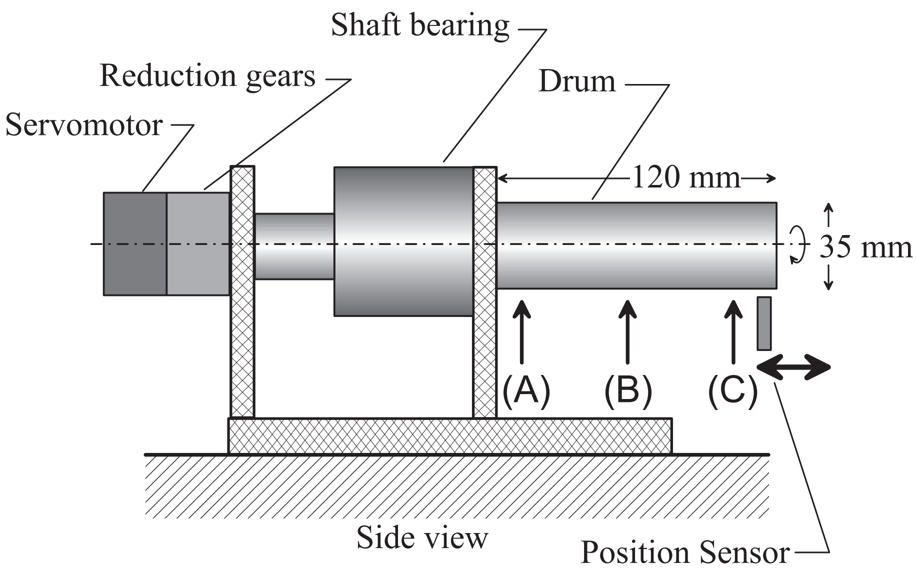


**Figure 7.** Structure of the overhung drum. Eccentricity of the drum was measured around points of (A)–(C).

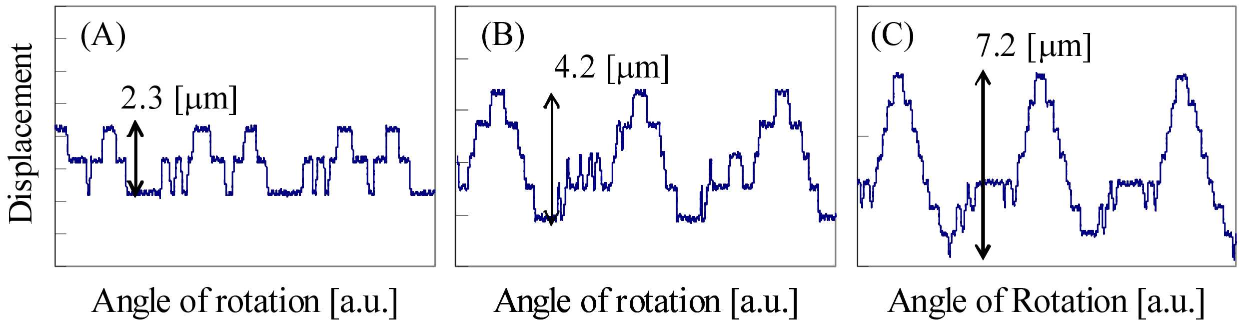


**Figure 8.** Eccentricity measured by eddy-current position sensor around points of (A)–(C) shown in Fig. 7

at the several distances from the bearing were measured by an eddy-current position-sensor, installed right under the drum. Fig. 8 shows displacement of the drum surface in rotating the drum. It is confirmed that measured eccentricity are not lager than the depth of focus ($\sim$ 10 $\mu$m) in any position along the rotation axis.

### 3.4. Printing a test pattern

Fig. 9 (b) is the photomicrograph of a printed test pattern, whose original image is shown in Fig. 9 (a). This test pattern with 480 $\times$ 200 multi-gray level pixels was printed in pitches of 1.5 $\times$ 3.0 $\mu$m. It is verified by this photograph that the multi-gray level image is successfully drawn by the constructed fringe printer.

## 4. RECONSTRUCTION OF PRINTED HOLOGRAMS

Fringe patterns of computer-generated holograms (CGH) were calculated and printed by the constructed fringe printer to verify its optical reconstruction. Table 1 shows the common parameters used for calculating and printing holograms.

Fig. 10 is optical reconstruction of the wire frame of a globe. The wire frame is composed by point sources of light in a density of 5,000 point/m. The fringe pattern with 16384 $\times$ 8192 sampling points (pixels) was printed in 1 hour and 9 minutes.

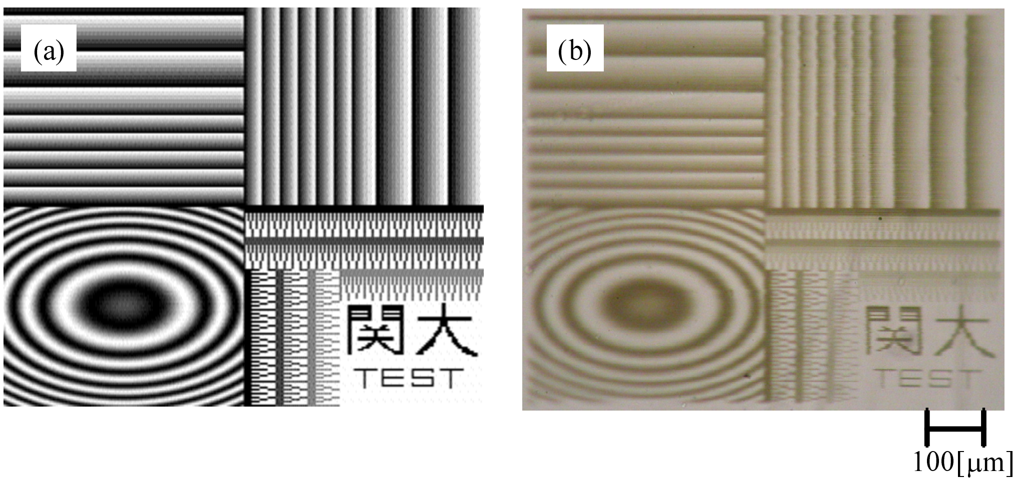


**Figure 9.** The photomicrograph of a test pattern (b) and its original image (a).

**Table 1.** Parameters and methods used for calculating and printing holograms.

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|---|---|
| Pixel size | 1.5 $\mu$m × 3.0 $\mu$m |
| Reconstruction wavelength | 632.8 nm |
| Object position from hologram | 100 mm |
| Density of point sources | 5,000 points/m (wire frame) |
| | 10,000 points/m (surface) |
| Calculation of spherical waves | Recurrence formula[1] |
| Coding | Point oriented coding |

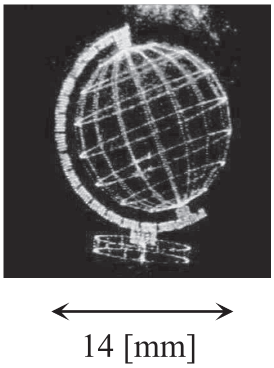


**Figure 10.** Optical reconstruction of the wire frame of a globe.

Fig. 11 is for a hexadecimal prism in the wire frame model again. This hologram consists of 32768 × 16384 pixels, and its dimension is approximately 50 mm square. The fringe printer finish printing the hologram in 2 h 24 m.

In the hologram shown above the object is a simple wire frame, i.e. spherical waves emitted from point sources placed along the wire frame are calculated and simply superimposed on the hologram plane. Fig. 12 also shows optical reconstruction of printed holograms but its object wave was numerically synthesized by another algorism. Objects of the hologram in Fig. 12 is composed of small planar surfaces, i.e. polygons. Furthermore, the hidden surfaces is removed by using the method of silhouette approximation.[9] The hologram consist of 16384 × 8192 pixels in Fig. 12 (a), while 32768 × 16384 pixels in (b).

## 5. CONCLUSION

We developed a printer system to print fringe patterns of digitally synthetic hologram, i.e. computer-generated holograms. The fringe pattern is printed on a photosensitive film pasted on a drum. Rotation of the drum provides raster-scan of laser spot. Optics of the fringe printer is simple and inexpensive, and therefore, a high resolution can be obtained easily. The constructed fringe printer actually reaches approximately 17,000 dpi × 8,500 dpi in resolution and is capable of printing a gray-level hologram of 5 cm square in 2 h 24 m.

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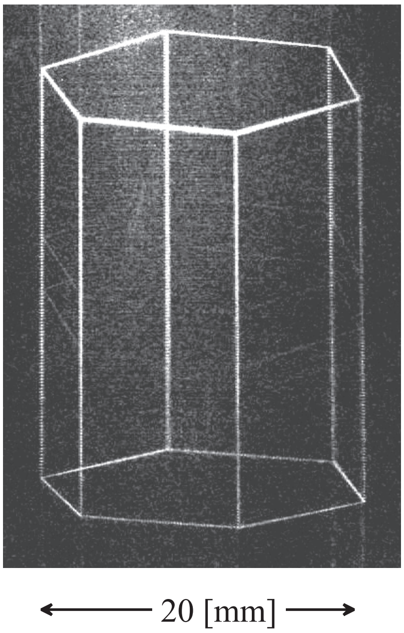


**Figure 11.** Optical reconstruction of the wire frame of a hexagonal prism.

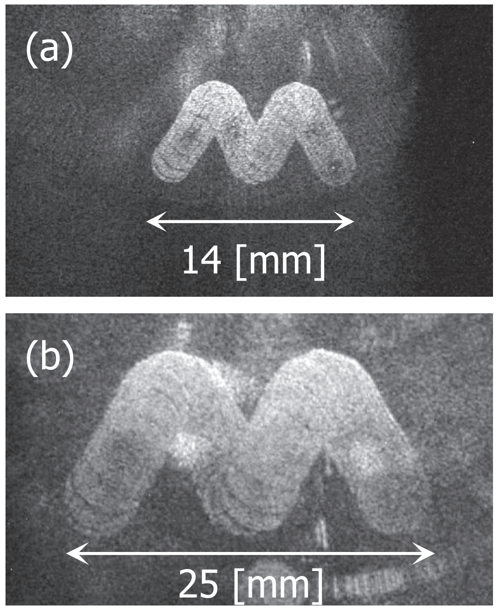


**Figure 12.** Optical reconstruction of surface-modeled spirals. The hologram is printed in 16384 × 8192 pixels (a) and 32768 × 16384 pixels (b).

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