

# Holographic enlarger with an afocal two-element system

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An afocal two-element holographic enlarger composed of two holographic lenses made as volume phase holograms on silver halide sensitized gelatin is analyzed. The magnification of the system and its maximum diffraction efficiency are: -4 and 55%, respectively. The imaging performance of the system is analyzed and some applications are briefly described.

## 1. Introduction

Holographic optical elements are diffractive elements and, therefore, they work by diffracting light from a generalized grating structure with nonuniform groove spacing. A result of this is that they present chromatic aberrations when polychromatic light is used during the reconstruction stage of the elements. However, it is possible to make a system of two holographic lenses where longitudinal and transverse chromatic aberrations can be corrected [1]. SHAKHER *et al.* [2] have shown that two holographic lenses can be used to image extended objects in white light. An enlarging system composed of a transmission holographic grating and a holographic lens (recorded as volume phase holograms) can be used to form images with incoherent light [3], but in these studies the authors use colour filters in their holographic systems. In a previous paper [4], we presented an experimental set-up of an afocal and partially achromatic system with two identical thick-phase holographic lenses which works with white light. In that afocal two-element holographic imaging system, the focal lengths of the lenses are equal and the magnification of the complex optical system is -1.

In this paper, we show a generalization of our previous afocal holographic optical system considering two thick-phase holographic lenses, with different focal lengths, positioned suitably to create also an afocal setup, and form an enlarging system. This holographic system forms a completely diffractive afocal telescope.

## 2. Experimental and discussion

The enlarging optical system was made with a combination of two transmission lenses as shown in Fig. 1. The first holographic lens  $L_1$  has a focal length

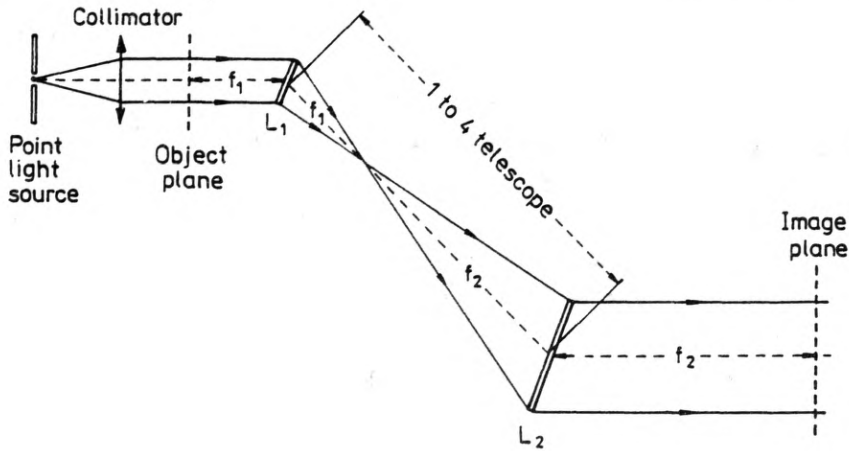


Fig. 1. Basic scheme for the afocal enlarging holographic optical system

$f_1 = 25$  cm for a wavelength of 633 nm, and an exit pupil diameter  $D_1 = 5$  cm ( $f$ -number:  $f/5$ ). For the second lens  $L_2$ , the focal length is  $f_2 = 100$  cm and the diameter is  $D_2 = 20$  cm ( $f$ -number:  $f/5$ ). The holographic lenses were recorded through the interference of a spherical wave from a point source and a plane wave as volume phase holograms in Agfa-Gevaert 8E75 HD emulsion, using the 633 nm radiation of a He-Ne laser. The object beam and the reference beam were of equal intensity. The point source was a pinhole of 25  $\mu\text{m}$  diameter and the plane wave was generated through a pinhole and a collimating lens (for  $L_1$ ) or through a pinhole and a spherical mirror (for  $L_2$ ). In order to minimize the effect of the astigmatism introduced by emulsion shrinkage, the lenses were recorded with the hologram normal along the bisector of the object-hologram-references angle (the accepted conventional symmetrical setup).

The holographic plates were processed as silver halide sensitized gelatin (SHSG) holograms [5]. With this processing technique it is possible to obtain transmission [6] and reflection [7] holographic optical elements with high transmittance within the whole visible spectrum and at the same time an optimum SNR. Maximum diffraction efficiency obtained for the holographic lenses was 75%. For that reason, diffraction efficiency of the complex system is better than 55% all over the image field.

As we can see from Figure 1, lens  $L_1$  was replayed by the conjugate of the plane recording wave, and the diffracted output beam was a converging wave. Thus,  $L_1$  acts as a focusing element, and the focus is a real image of the point source. However, lens  $L_2$  was illuminated by a divergent spherical wave, the final output beam was collimated and  $L_2$  acted as a collimator. Lenses  $L_1$  and  $L_2$  were separated by a distance corresponding to the sum of the focal length of each of them (this distance was 125 cm for a 633 nm illuminating wavelength). The magnification of the system  $m$  can be written as  $m = -f_2/f_1$ , and as  $|f_2| > |f_1|$ , then  $|m| > 1$ . In this configuration, the two holographic lenses form an enlarging system and it is an

afocal telescope: a bundle of parallel rays entering the entrance pupil of the system leaves the exit pupil also as a parallel bundle. The holographic system has an entrance aperture of 5 cm and a magnification of  $m = -4$ , and the system can be used to form a magnified image of an input transparency (the enlarging system acts as a two dimensional signal scaler [2]). Obviously, the negative magnification indicates an inverted image.

On the other hand, the enlarging system can work with white light as the holographic doublet analyzed in [4]. We can select a particular wavelength filtering the image from the first lens on the focal plane by means of a suitably sized diaphragm. In this situation, we can illuminate the first holographic lens with a collimated beam of white light and we place a diaphragm at a distance and under an angle corresponding to a selected wavelength (the focal length and the Bragg angle for this wavelength, respectively). If the distance between this aperture stop and the second lens is the focal length for this lens and for the same wavelength, then the image wavefront emerging from the afocal holographic system is collimated and of partially coherent light. The coherence is a function of the diameter of the aperture stop. However, the magnification of the system does not change when we vary the reconstruction wavelength. Using this device we can obtain collimated beams for different wavelengths and bandwidths by choosing the reconstruction angle, the relative position of the holographic lenses and the position and size of the aperture stop. These collimated beams will have a large diameter ( $\sim 20$  cm) and high diffraction efficiency all over the exit pupil of the system.

In order to analyze the quality of the image beams obtained with this enlarging optical system and its imaging performance, we can obtain the resolution of the system when we work with a He-Ne laser in the reconstruction of the holograms. This will be the best resolution of the enlarging system because if we use other reconstructing light sources (such as monochromatic but of different wavelength, of broad spectral bandwidth or white light), the resolution will be less than when using the same wavelength as during the recording stage of the lenses. This is due to the increase of aberrations in the reconstructed images [8]. In order to show a visual result, imaging at finite distances was performed. The object used in this study is the USAF three-barr resolution target placed in the back focal plane of the lens  $L_1$  and illuminated with 633 nm radiation. The distance between the test target and the lens  $L_1$  thus was the focal length  $f_1 = 25$  cm and the distance between the lens  $L_2$  and the image plane was the focal length  $f_2 = 100$  cm (Fig. 1). The resolution test chart was imaged through the enlarging holographic optical system and in Fig. 2 we present a photograph of the final image of the resolution test chart in the front focal plane of the lens  $L_2$ . Moreover, we observed this image through a  $10\times$  microscope objective and we found that the maximum resolution of this afocal telescope system was almost 40 lines/mm.

This enlarging system can work as a telescopic system with both its object and image at infinity. However, it can also work as an imaging system with the object placed at a finite distance from the first lens. The system's behaviour will be different for each of these two cases.

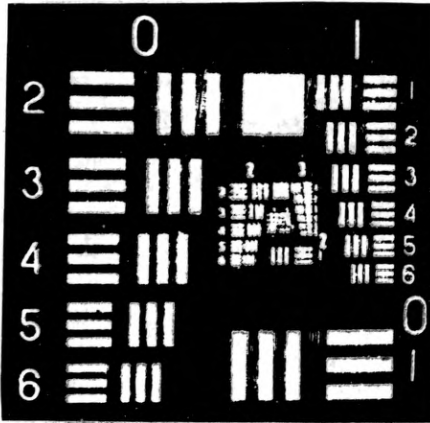


Fig. 2. Photograph of the enlarged image of the resolution test chart when the holographic enlarger system is reconstructed with a He-Ne laser

When the enlarging system works as a telescopic system, due to its geometric parameters, both  $L_1$  and  $L_2$  can serve either as the field stop or the aperture stop. In this case, the holographic system's parameters would have to be adjusted to include a stop between the two lenses at the focal distance  $f_1$  of the first lens. By doing this, the stop would act as a field stop, while the first lens would serve as an aperture stop. In this type of situation angular fields must be used, and in order to calculate these angular fields we must also know the focal distance of the first lens  $f_1$  and the radius  $R$  of the stop which was introduced between the two lenses. The angular field will be calculated using the equation:  $\tan \alpha = R/f_1$ , where  $\alpha$  is the angle between the optical axis and the principal ray passing through the edge of the field stop of radius  $R$ .

When the enlarging system works as an imaging system with its object situated at a finite distance from the first focal plane along the axis (which is what happens with the target test), the  $L_1$  lens acts as an aperture stop as well as an entrance pupil, and lens  $L_2$  acts as a field stop and exit window. Since the entrance window is located in front of the object, the system will suffer from vignetting. However, once the full, half and limit fields of illumination are calculated — always keeping the geometrical data of the system in mind — we find that if the object is smaller than  $\sim 3$  cm and if it is centered on the axis of the first lens, we will always be working in the field of full illumination and no vignetting will appear. This is what happens with the test target, which is  $\sim 1$  cm in size, thereby making it possible to obtain images like the one seen in the photograph (Fig. 2).

### 3. Final remarks

The enlarging holographic optical system described works under coherent, partially coherent and white light illumination conditions with good experimental results. The system can form high-quality enlarger images that are quite bright since the

component lenses have quite high diffraction efficiency and low noise due to optimum characteristics of the SHSG as holographic recording material.

The limit of resolution of the system has been obtained using the same coherent light source that we used to record the component holographic lenses and a maximum resolution of  $\sim 40$  lines/mm has been achieved.

This enlarging system can be used for filtering white light obtaining uniform collimated beams of partially coherent light with different wavelengths as we showed in a previous paper [4], but now these beams will have a large diameter ( $\sim 20$  cm).

Finally, it will be possible to copy large size holograms with partially coherent light [9] in areas of the spectrum where no adequate lasers exist by using this holographic enlarging system.

*Acknowledgements* – The authors would like to thank the reviewer of this paper for his useful suggestions and for his comments, which significantly improved the original manuscript.

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*Received February 10, 1993  
in revised form April 30, 1993*