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Optics & Laser Technology 39 (2007) 1496–1503
Optics & Laser Technology
www.elsevier.com/locate/optlastec

Spatial-frequency-filtering effect of multiphase holograms

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Received 7 July 2006; received in revised form 29 January 2007; accepted 29 January 2007
Available online 21 March 2007

Abstract

A well-designed hologram can be used as a spatial frequency filter to remove moiré fringes in a digital imaging system. However, it also degrades the resolution of the image. We have used a homemade program to design holograms with better filtering characteristics. We have designed holograms with two, four, eight, and 16 phases and compared their diffraction efficiencies and modulation transfer functions (MTFs). The four-phase hologram showed a diffraction efficiency and MTF characteristics similar to those of the binary hologram. The eight-phase hologram, however, showed much better diffraction efficiency than the previous two, and thus higher MTF values. The 16-phase hologram was still better, but the improvement was marginal. We have manufactured binary and eight-phase holograms and measured their MTFs. We have also observed directly their filtering effects by attaching them to a digital camera and taking pictures of test charts. The Moiré-fringe-removing effects of the two holograms were similar, but the eight-phase hologram showed better resolution.

Keywords: Spatial frequency filter; Computer-generated hologram; Modulation transfer function (MTF)

1. Introduction

A digital imaging device, such as a charge-coupled device (CCD) or a CMOS image sensor, samples an image by means of finite-size image cells. According to sampling theory, perfect image restoration is possible when the incoming image has no spatial frequency component above the Nyquist frequency, which is half the inverse of the sampling period, or pixel size [1,2]. When the incoming image has frequency components larger than the Nyquist frequency, image distortion originating from aliasing is inevitable [3,4]. False Moiré fringes also appear when the incoming image has high-spatial-frequency components. Therefore, low-pass filters are used in digital imaging systems such as digital cameras to filter out high-spatial-frequency components.

The performance of a spatial frequency filter can be seen from its modulation transfer function (MTF). In an imaging system, the MTF of a filter can be obtained from the Fourier transform of the intensity distribution on the image plane when the object is a point source [5]. An ideal low-pass filter would remove all spatial frequency components that are higher than the Nyquist frequency and pass all that are lower than the Nyquist frequency, as in Fig. 1. However, it requires negative Fourier coefficients to obtain the ideal MTF graph. Since a light intensity cannot be negative, the ideal filter cannot be realized.

The most widely used filter is the birefringent low-pass filter (BLF), which divides the incoming beam into four beams [6,7]. The Fourier transform of the intensity distribution produced by a BLF yields a characteristic MTF, also shown in Fig. 1. Usually, a BLF is designed to match the point where the value of the MTF becomes zero to the Nyquist frequency. Therefore, the resolution degradation is not severe, since the MTF is rather large below the Nyquist frequency. However, a BLF is not effective for Moiré filtering, since the value of the MTF above the Nyquist frequency is also large. Another shortcoming is that a BLF is expensive and is too thick to use in small imaging modules such as mobile phone cameras, since it is made of two crystal plates.

Recently, there have been some studies on the characteristics of gratings [8,9] used as spatial frequency filters. Since

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doi:10.1016/j.optlastec.2007.01.005

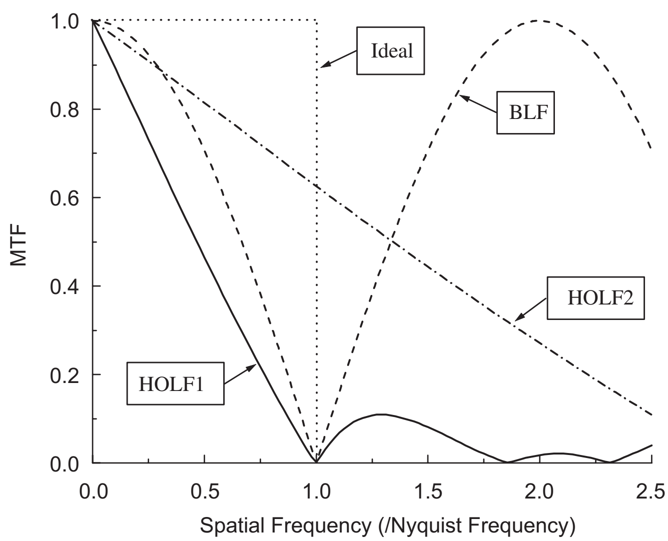

Fig. 1. MTF graphs for several filters (BLF, birefringent filter). HOLF1 and HOLF2 are two-phase holographic filters of the same structure but different period.

a grating can be implemented by means of thin films on a glass surface, it is thin and cost-effective. A thin hologram also has this merit. The grating or hologram is located between the camera lens and the CCD. It widens the image of a point object to the size of pixel size. Therefore, the period of a diffractive filter is determined by the pixel size and the distance between the filter and the CCD.

We have reported experimental results for a two-phase computer-generated hologram [10]. A graph of the MTF of this hologram low-pass filter (HOLF) showed a linear decline in the low-spatial-frequency region. Therefore, if we set the cutoff frequency equal to the Nyquist frequency, as in the case of HOLF1 in Fig. 1, the loss in the pass band results in resolution degradation. If we set the cutoff frequency higher, as in the case of HOLF2, to enhance the resolution, which can be achieved by increasing the period of the hologram, the high-frequency filtering effect decreases and the device no longer plays its role as a filter. Therefore, the MTF must have a convex shape in the pass band to meet the requirements of resolution and filtering.

For a smooth, convex-shaped MTF graph to be obtained, the filter must disperse the incoming light into a finite-size region. For example, a BLF divides the incoming beam into four beams only. However, we cannot distribute 100% of the incoming beam into a finite region with any hologram; unwanted higher-order diffraction exists, and this causes a linearly decaying MTF graph in the pass band. To make a HOLF with a convex MTF in the pass band, the diffraction efficiency must be improved.

We have designed and tested HOLFs to achieve better MTF characteristics. In Section 2, the hologram design process is reported. In Section 3, we describe the dependence of the diffraction efficiency and the MTF on each design parameter. The manufacture of the HOLFs and the measurement of their filtering characteristics are described in Section 4. The installation of a HOLF in a real camera is described in Section 5.

2. HOLF Design

The MTF of an optical low-pass filter is determined by the intensity distribution in the image plane, which is the Fraunhofer diffraction pattern in the case of a HOLF [5,11]. We have used a homemade program to design a hologram whose diffraction pattern approaches a given goal image. The hologram is assumed to be periodic. The program divides the period of the hologram into smaller cells and assigns a phase to each cell. We assume a square-shaped hologram, and the same number of cells in the x and y directions. Therefore, each cell is square. The smaller the cells are into which we divide the period, the better the chance of improving the diffraction efficiency, but we may need more computing time.

If we use a lithography process with n mask steps, we may specify 2^n phases at most. Therefore, the total number of phases is assumed to be 2^n ($n = 1, 2, \ldots$). The values of the phase for a binary hologram are $-\pi/2$ and $\pi/2$, and those for a four-phase hologram are $-3\pi/4$, $-\pi/4$, $\pi/4$, and $3\pi/4$. In general, an n-phase hologram may have phases equal to $(2m-n-1)\pi/n$, $m = 1,2,\ldots n$.

To design a hologram, we must input the goal diffraction pattern. The role of a HOLF in a digital camera is to disperse the incoming light in order that the image of a point object is expanded to a finite size. The size must be similar to the pixel size of the CCD to eliminate the frequency components near the Nyquist frequency. Hence the goal diffraction pattern of the HOLF is of such a shape that only the diffracted beams in a certain area are nonzero. The width of this area depends on the period of the HOLF and the parameters of the imaging system. To obtain higher diffraction efficiency, nearly circular shape is taken as the goal pattern.

The goal diffraction pattern must, however, be formed by discontinuous dots, since the hologram is periodic. If the number of dots in the goal pattern is large, the distance between the dots must be small and hence the period of the HOLF must become large. If the period of the HOLF is too large, only a small number of periods may be illuminated in the imaging system. If the number of dots in the goal pattern is too small, the period of the HOLF becomes so small that a shadow of the HOLF can be seen in the imaging system [9]. A choice of 21 dots, as in Fig. 2(a), is suitable as a goal for the present. The dots make nearly circular diffraction pattern. Since the dots have uniform intensity values, the goal pattern has symmetries such as rotation (90°), inversion, mirror images, etc. The dots can have non-uniform intensity distribution such as Gaussian. But it is found out that the diffraction efficiency was little affected by the distribution pattern.

After the goal pattern, the number of hologram cells, and the number of phase steps have been determined, the optimization process begins. We have used a Monte Carlo