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Abstract: The effects of illuminating beam profile (Gaussian, tophat) and fill-factor (underfill or overfill) on digital holographic image contrast and modulation transfer function are evaluated by numerical simulation and compared with experimental measurements.

OCIS codes: (090.1995) Digital holography, (140.3300) Laser beam shaping, (110.3960) Microlithography

1. Introduction

Digital holography based on phase-only spatial light modulators (SLMs) has seen tremendous growth, with applications ranging from exquisite biological measurements, to holographic optical tweezers (HOT) and holographic lithography[1,2]. One of the key advantages of phase-only holographic light shaping is the greater efficiency of incident light utilization[3]. Intuitively, phase-only modulation (which redirects light energy to desired image areas) should have fewer losses than amplitude modulation (in which energy in dark areas is blocked or attenuated), but practical constraints may offset these theoretical advantages.

To support this surge in interest, many investigators have focused their efforts on characterization and calibration of the SLM's phase response, but the characteristics of the incident illumination have received little consideration. Nearly all investigators reporting on SLM-based holographic image projection use TEM_{00} Gaussian laser beam illumination, sometimes specified to be "slightly overfilled[4]." The size of the laser beam relative to the SLM active area strongly affects the overall system efficiency, imposing a trade-off with illumination uniformity, but quantitative optimization of these parameters has not been reported. As a potential solution, a variety of commercially available refractive beam-shapers are able to convert Gaussian profiles to tophat, while preserving the beam's phase front[5], which points to the need to determine an optimal illumination profile for holographic image projection.

Here we seek to assess the influence of key source beam parameters, such as profile shape and fill-factor and on the quality of projected holographic light fields. This investigation represents a set of key considerations for system-level design parameters to allow digital holographic tools to progress beyond being laboratory demonstrations. Our interest is in optimizing this technology for lithography applications, where the contrast between exposed and unexposed areas is a key performance metric, as is the system's spatial resolution. Quantitation of image quality is critical to properly evaluate design trade-offs. In general, quantitative image quality is much more often measured for simulated or computed holograms than actual projections. Some image quality metrics have been proposed[6,7], to which we add the measurement of the modulation transfer function (MTF) as a direct resolution measurement.

In this study, we use a phase-only parallel-aligned nematic (PAN) liquid crystal on silicon (LCoS) microdisplay as our SLM, since these types of devices are rapidly growing in popularity and seeing significant advancements in quality. We use both numerical simulation as well as experimental measurements of the projected light fields to seek out the conditions that produce the best hologram quality. Specifically, we compare the uniform illumination of a tophat beam with Gaussian beam profiles at different overfill ratios. An overfill factor of 1 is defined as being a Gaussian beam whose $1/e^2$ intensity diameter (4σ) is matched to the diagonal dimension of the SLM. Larger beam overfill ratios represent more uniform intensity, with the limiting case being the completely uniform tophat profile.

2. Methods

Simulations: Numerical holographic reconstruction (Matlab, The Mathworks) is carried out using simple 2D FFT transforms of complex-valued optical fields, convolved with the calculated point-spread function of the projection lens. The phase component of the complex fields is the computer generated hologram (CGH) calculated with 60 iterations of the Gerchberg-Saxton (G-S) algorithm[8], while the amplitude is derived from either a uniform (unity) or Gaussian intensity profile. During G-S iterations, both Gaussian and tophat illumination profiles are incorporated, and the relative hologram quality assessed. Additionally, two approaches for displaying the CGH on the 1920×1080-pixel SLM are compared – a crop of a full-size 1920×1920-pixel CGH, and a tiling of a 1080×1080-pixel CGH (cropped to fit into the 1920-px dimension).

The computed holographic projection of the pattern used for measuring contrast and MTF is shown in Fig. 1(a). The pattern includes pure white and black squares (outlined by blue and red boxes, respectively), and the ratio of their mean intensities is computed as the contrast. The large quadrants contain sinusoidal gratings with spatially-varying frequency, used as the basis for estimating the MTF along both the X and Y directions.

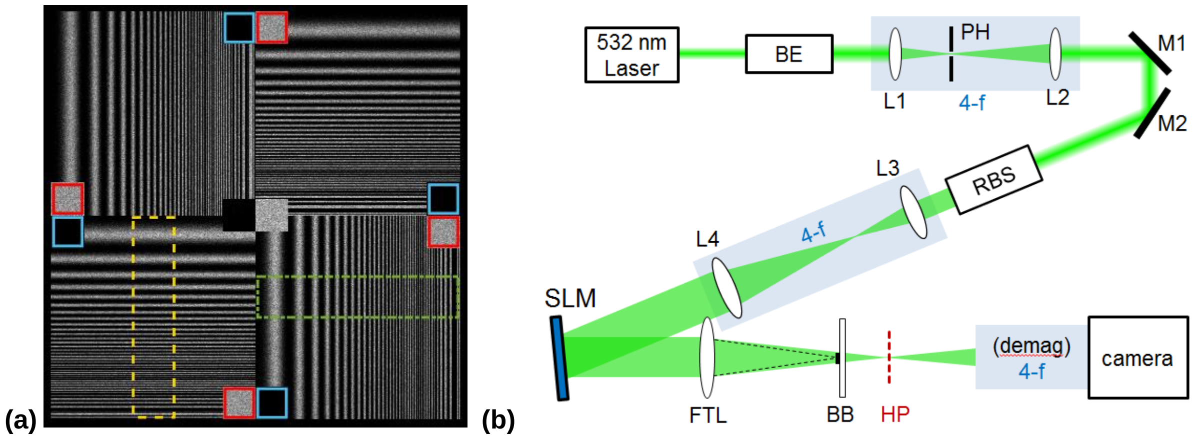

Figure 1: (a) The projected test pattern used for evaluating image contrast and system MTF. (b) Sketch of system layout for experimental hologram evaluation. Blue-shaded rectangles are image-relay Keplerian telescope lens pairs. BE: variable beam expander, PH: pinhole spatial filter, RBS: refractive beam shaper, FTL: Fourier transform lens, BB: beam block for undiffracted light, HP: hologram imaging plane

Experimental: The optical layout in Figure 1(b) is used to carry out experimental evaluation of hologram quality. A 532 nm DPSS laser (Coherent Verdi V6) is expanded in two steps to the correct size for the entrance pupil of a refractive beam shaper (RBS, πShaper, AdlOptica), on the way passing through a 25 µm pinhole spatial filter to improve the beam circularity. The tophat profile output of the RBS is image-relayed by an expansion telescope to illuminate the SLM (PLUTO VIS, HOLOEYE Photonics). For Gaussian beam profiles, the RBS is removed, and a range of beam overfill conditions are obtained by switching out L3 and repositioning it appropriately.

The CGH is then projected through a f=250 mm Fourier transform lens (FTL), with a high-pass beam block at the lens focal plane, removing undiffracted light that focuses at the center spot. The holographic phase patterns displayed on the SLM are the same as those used to generate numerical reconstructions, with spherical phase added to displace the hologram focal plane beyond the Fourier lens focal plane by approximately 30 mm. This creates clean holographic reconstructions virtually free of undesirable content. The reconstructed light fields are imaged for quantitation by a 1.67x telescope onto a CMOS camera (GO-5000M, JAI), adjusting exposure durations to accommodate the dynamic range of the camera for each beam fill condition.

Captured images are analyzed in Matlab to determine the contrast and MTF. Contrast for experimental images is computed similarly to simulated images, as the ratio of the mean intensities of the red and blue areas in Fig. 1(a). MTFs for the X and Y direction are calculated from intensity data in the areas outlined by the dotted green and yellow boxes in Fig. 1(a). Image intensities are first averaged along the short dimension of the rectangle to produce a single line-scan, representing the reconstruction of the spatially varying sinusoid. The MTF is calculated as follows: MTF=$(i_{max}-i_{min})/(I_{MIN}+I_{MAX})$, where i_{max} and i_{min} are the maximum and minimum intensity values of each fringe, and I_{MAX} and I_{MIN} are the global maximum and minimum for the entire line-scan.

3. Results and Conclusions

Contrast measurements from simulated hologram reconstructions are shown in Fig. 2(a), with experimentally measured contrast in Fig. 2(b). The key conclusion from these results is that the RBS yields no image contrast benefit over non-uniform Gaussian illumination intensity. In fact, experimental measurements indicate a weak trend of lower image contrast when using more uniform beam profiles.

Concerning the tiling of a smaller hologram across the SLM, which is done to mitigate beam non-uniformity [9], our simulations imply that the 1080×1080 tiled CGHs may yield significantly lower contrast and much greater noise (as represented by larger error bars). However, experiments do not support this conclusion at present. Likewise, no significant difference is found between using Gaussian and tophat intensity profiles during G-S iterations for CGH calculation, except for the simulations for 1920×1920 hologram. This warrants further investigation, by including more accurate diffraction physics in the simulations, as these currently represent only an idealized best-case limit. The noise characteristics of these CGH projections are also not fully represented by these data. For instance, qualitatively, the image reconstructions from 1080×1080 tiled CGHs do appear noisier, suggesting that adding a separate noise metric (such as peak SNR suggested by Yoshikawa[7]) may be useful here.

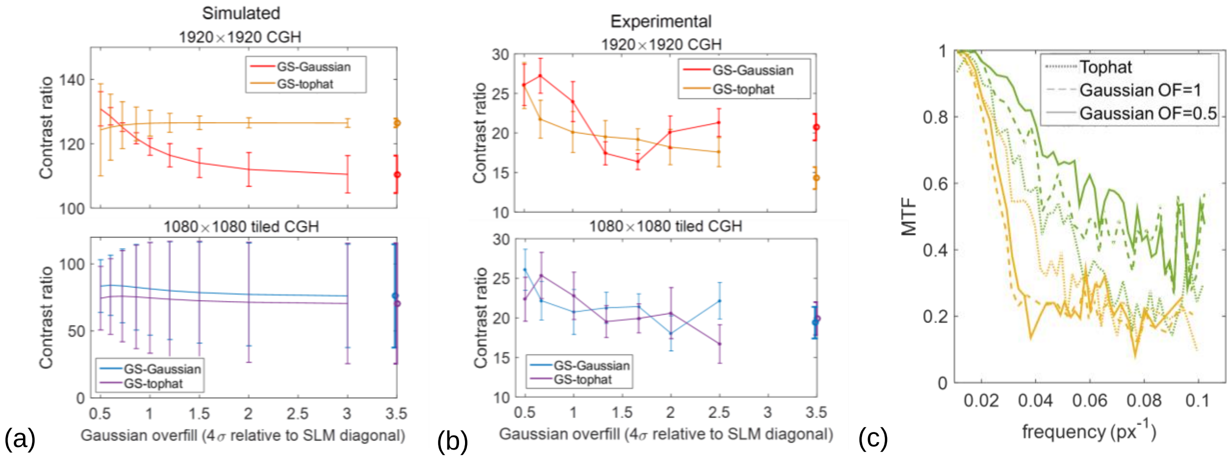

Figure 2: Contrast ratios of (a) simulated and (b) experimentally measured hologram projections. In all plots, error bars indicate the standard deviation of the mean intensity ratio. Contrast values resulting from tophat illumination during CGH projection are plotted at the right-most edge of the graph with heavier symbols and error bars. (c) Comparison of MTF measurements when projecting a 1920×1920 pixel CGH (generated with tophat illumination during G-S algorithm iterations) at different beam fill factors. Green curves are for the X-direction and yellow curves for the Y-direction.

Measuring image MTFs, however does provide useful additional detail. A selection of MTF plots are shown in Fig. 2(c). In all cases, as expected, the MTF along the Y direction (yellow) drops off faster than that for the X direction (green). This can be attributed to the smaller SLM pixel count along the Y dimension. However, we find the unexpected result that the use of more uniform beams produces X and Y MTFs that are more similar to each other, with nearly identical curves for tophat illumination. Thus, tophat illumination does provide a significant benefit to resolution along the short dimension of the rectangular SLM.

It is important to note that the these measurements do not account for overall efficiency of light utilization (and therefore overall hologram brightness), which is lower for greater beam overfill ratios. Therefore, in cases where light usage is at a premium, Gaussian beams with lower overfill ratios and reduced beam uniformity are preferable. The increased alignment stringency that an RBS imposes is only worthwhile in very particular cases in which maximizing the SLMs resolution is critical.

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