

Mass-producible micro-holographic tags

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Abstract

Microtags are microscopic computer-generated holograms with 130-nm features and are mass-producible with EUVL. This fabrication method renders microtags difficult to counterfeit. Applications include tagging and tracking of microprocessors, memory chips, currency, and credit cards.

Keywords: microscopic computer-generated holograms, anti-counterfeiting measures, extreme ultraviolet lithography (EUVL)

Introduction

The microtag concept has been developed for security purposes. Microtags can be mass-produced by using an advanced extreme-ultraviolet lithography (EUVL) tool currently under development at Sandia/Livermore. This method of fabrication results in features small enough (down to 100 nm) to deter most attempts at counterfeiting. Microtags may therefore be used to protect microprocessors, random-access memory (RAM) chips, currency, and credit cards.

Microtags are microscopic, computer-generated holograms. The dimensions of a microtag are on the order of 80 μm or approximately the size of a speck of dust. The information encoded in a microtag can be retrieved by illumination of the microtag in a near-Littrow configuration with a laser source (see Fig. 1). When the microtag is located in the front focal plane of a read-out lens then the decoded information, the magnitude of the microtag's Fourier transform, may be found at the lens's back focal plane (see Fig. 2). This pattern can be viewed by eye or recorded by a digital imager.

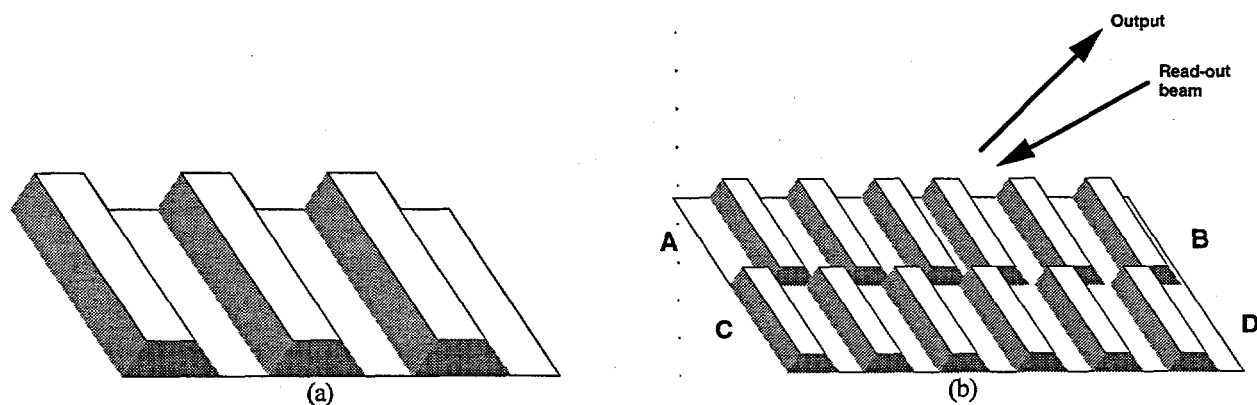
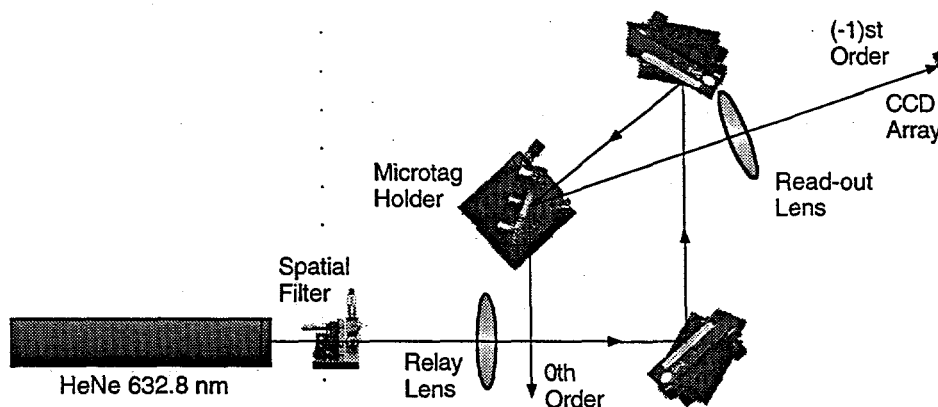


Figure 1. The near-Littrow read-out configuration. Part (a) of the figure schematically illustrates an individual constant-phase cell. Part (b) shows the read-out geometry and the scheme for encoding phase by cell translations. See text for further details.

Simple alphanumeric characters and two-dimensional binary codes can for example be encoded in microtags consisting of 16×16 constant-phase cells. Each constant-phase cell is a linear grating that diffracts the read-out beam into the (-1)st order. Figure 1(a) schematically presents an isometric view of a grating that can be formed in photoresist. The wall slope associated with each grating line can be adjusted to maximize the amount of radiance in the diffracted output beam.

Figure 1 also shows an array of four constant-phase cells (marked A-D). The relative phase difference between cells is encoded by translating each cell a fraction of the grating period.¹ For example, there is a phase difference of π radians between cells A and C and no phase difference between cells C and D. These phase differences can be optimized to result in a desired far-field irradiance pattern.

Figure 2. Microtag readout system. This figure shows the current version of the readout system, utilizing a HeNe laser source. The relay and read-out lenses are actually commercially available doublets. The angle between the read-out and output beams has been exaggerated for clarity.



Microtag System Design

A prototype system including the microtag geometry, the test patterns, and the readout system had to be conceived all together. The goal of this program was to develop a microscopic, difficult-to-forge tag that could be mass-produced with an EUV lithography tool. The design constraints are listed in Table 1.

Design Constraint	Specification
Feature dimension, d	$250 \text{ nm} > d > 100 \text{ nm}$,
Readout system	straightforward, based on off-the-shelf components,
Maximum dimension of microtag	$80 \mu\text{m}$, i.e. comparable to a speck of dust.

Table 1. The essential microtag system design constraints.

The near-Littrow read-out configuration and the shortest possible read-out wavelength were chosen because the combination requires extremely narrow grating line widths. Such narrow features make microtags very difficult to forge. For example, if the read-out beam and the diffracted output beam are both 60° from the grating normal and the read-out wavelength is 440 nm (HeCd laser), then the feature widths must be approximately 130 nm wide. The capability to print such small feature sizes will not be commonly available for another 10-20 years. The only current method capable of fabricating a microtag with comparable feature dimensions is an electron-beam writer. However, this option is slow and expensive.

Microtags may be employed in two differing ways. On the one hand, advantage can be taken of their microscopic size in order to make microtags very difficult to locate. On the other hand, we can rely on the difficulty of forging microtags with currently available techniques and print large collections of microtags, for instance covering an area $2 \text{ mm} \times 2 \text{ mm}$. In the first case, the first problem is finding the microtag. The second problem is read-out of the microtag which requires illumination from the correct azimuth and incidence angles at the right wavelength (see Appendix). In the second case, a large collection of microtags can include microtags of different orientations and slightly different line widths (120 nm, 130 nm, 140 nm, etc.) so that the read-out azimuth and diffraction angles associated with each microtag differ. On an array of microtags, position can also be used to encode information. With multiple microtags, one could for instance spell out words. Whatever the method of encoding information, this "flaunt 'em" scheme may be safer than reliance on small size alone. A potential forger will need to first decode and then write an awesome amount of information. The complexity of these microtag collections can be determined by the expected capability that a counterfeiter may possess to read out and then copy a microtag collection onto every forgery.

The readout system itself has been designed and built out of off-the-shelf lenses, mounts, and a commercial charge-coupled device (CCD) camera (see Fig. 2). The simplest, readily obtainable optics capable of diffraction-limited imaging are doublets of modest speed, e.g. F/4. Choices for the read-out lens's focal ratio, focal length, and the area of the region of interest (ROI) in the far field then dictate the dimensions of the microtag.

Sample Microtag Designs

Fast Fourier Transform Sampling Considerations

For the initial design effort, we have assumed the use of a HeNe laser, as shown in Fig. 2. Table 2 shows the remaining relevant parameters and their associated values. We decided on a 16×16 cell, constant-absolute-value-reflectance microtag as a starting point. Each cell was twice oversampled in the x and y directions, resulting in

$$\Delta x = \Delta y = 5 \mu\text{m}. \quad (1)$$

The 32×32 samples microtag was then placed inside a 256×256 array, assuring a very extensive "guard band" (see Figure 3). The sampling interval in the plane of the CCD array is consequently given by

$$\Delta x' = \Delta y' = \frac{\lambda f}{256 \Delta x} = 25 \mu\text{m}, \quad (2)$$

which equals the pitch of the detector elements.³

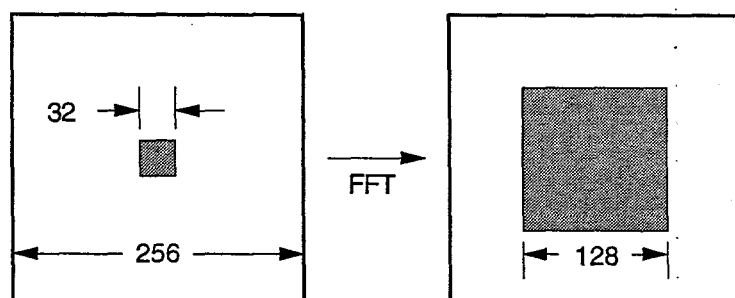


Figure 3. Data array and microtag and ROI dimensions in samples. The microtag occupies a 32×32 samples region in a 256×256 data array. Each cell on the tag is twice oversampled. The resultant sampling interval in the far-field equals the pitch of CCD detector elements [Eq. (2)]. The ROI is 128 samples (detectors) on a side.

Prototype Parameters	Specification
HeNe laser source	$\lambda = 632.8 \text{ nm}$
CCD camera detector element size	$25 \mu\text{m} \times 25 \mu\text{m}$
Read-out lens focal length, f	50.5 mm
Microtag cell dimensions	$10 \mu\text{m} \times 10 \mu\text{m}$

Table 2. Key parameters associated with the initial microtag design.

The extent of the ROI in the far field is dictated by the size of individual microtag cells (see Table 2). The cells are rectangular when viewed at normal incidence but appear square at the read-out angle of incidence, hence the entry in Table 2. In a fashion similar to Eq. (2), we obtain a region-of-interest 3.19 mm on a side. This size fits well into standard CCD array configurations ($6.6 \text{ mm} \times 8.8 \text{ mm}$, for instance). At the same time, given the detector-element size of $25 \mu\text{m}$, the far-field irradiance pattern will be oversampled with 128×128 detector elements contained in the region of interest (see Fig. 3). Since it is impossible to control so many samples within the ROI with a 16×16 microtag (the space-bandwidth product argument), some form of averaging of detector outputs or sparse sampling will need to be employed prior to far-field pattern identification. In the design examples described below, the CCD array outputs have been averaged in groups of 8×8 pixels. Each group is referred to as a *super-pixel*.

Figures 4 and 5 show two example microtag designs and the associated far-field irradiance patterns. The designs were obtained using the Iterative Fourier-Transform Algorithm (IFTA).² In both cases, the absolute value of the reflectance at

each constant-phase cell is the same across the microtag. The phase values associated with each cell have been quantized into 39 levels. This level of quantization is determined by the accuracy of the reflective-mask fabrication process.

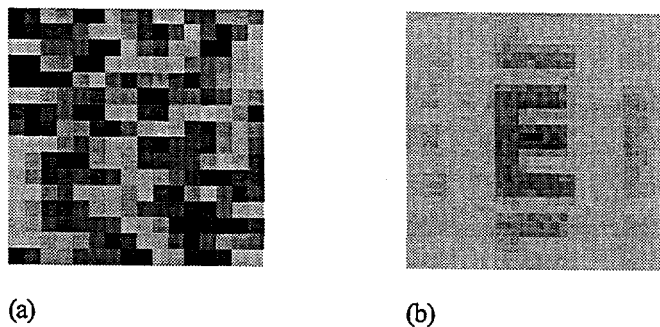


Figure 4. A 16×16 array of constant-phase cells and the corresponding predicted far-field irradiance pattern.

Figure 4(a) shows an example 16×16 cells microtag. Phase values are shown, ranging from 0 radians (dark) to 2π radians (light), not inclusive. A negative of the calculated irradiance pattern in the read-out lens's rear focal plane is illustrated in Fig. 4(b). The region of interest consists of a 16×16 super-pixel area, centered within the image. The super-pixels indicated in Fig. 4(b) consist each of an 8×8 CCD-pixel neighborhood. The value associated with each super-pixel is the average of the 64 pixels belonging to it.

Given the sampling and Fourier transform parameters listed in Table 2, this ROI corresponds to a $3.19 \text{ mm} \times 3.19 \text{ mm}$ region on the CCD array.

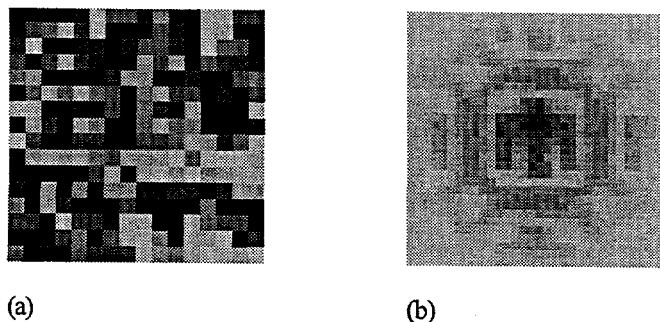


Figure 5. A 16×16 array of constant-phase cells and the corresponding predicted far-field irradiance pattern.

Figure 5(a) shows another example 16×16 cells microtag. Phase values are shown, ranging from 0 radians (dark) to 2π radians (light), not inclusive. A negative of the calculated irradiance pattern in the read-out lens's rear focal plane is illustrated in Fig. 5(b). The region of interest consists of a 16×16 pixel area, centered within the image. The desired far-field irradiance pattern in this case is the Sandia logo, a thunderbird. Figure 5(b) shows the CCD output after pixel averaging as described above.

Extreme-UV Lithography

Sandia National Laboratories and AT&T have built an experimental extreme-UV lithography system at Sandia's Livermore, California, facility. This system uses a laser-plasma source of 13.4-nm radiation for illumination. The all-reflective Schwarzschild camera, using Si-Mo multilayer coatings, images a reflective mask onto a wafer with a tenfold minification. The camera can faithfully reproduce images containing 100-nm features (see Fig. 6). Very good image quality and low distortion can be maintained over a $400\text{-}\mu\text{m}$ image field. Several photoresists are available, including poly(methylmethacrylate) (PMMA).

A next-generation, large field-of-view system is under development.⁴ The associated ring-field camera is designed to have a 25-mm-long field that is "pushbroom"-scanned thus forming a $25\text{-mm} \times 25\text{-mm}$ image field. This capability will allow the printing of multiple microtags, to spell out words or encode information through binary codes. These microtags can all have different orientations and grating frequencies thus varying the read-out azimuth and elevation angles.

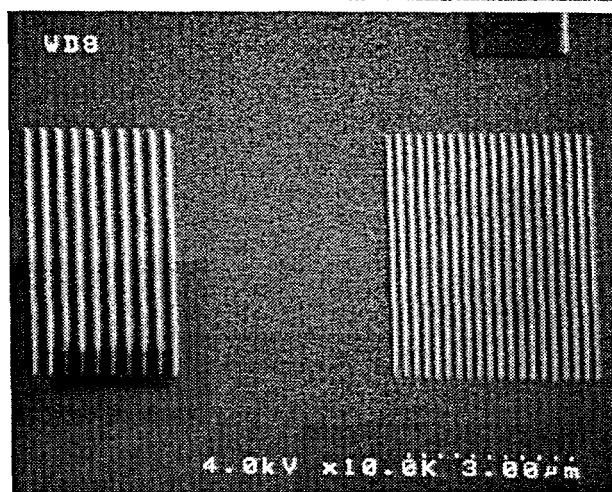
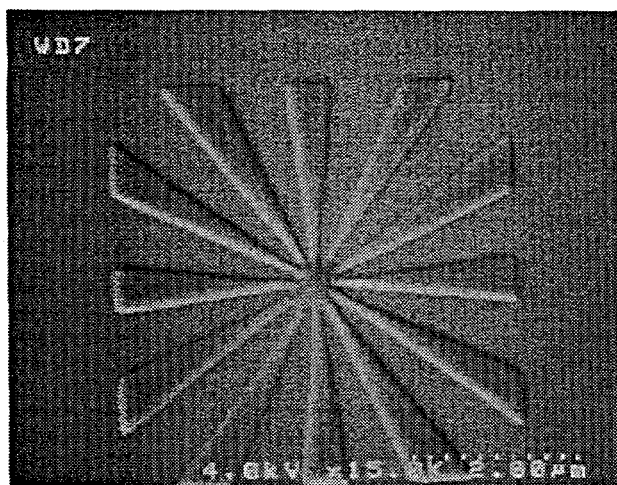


Figure 6. Examples of 100-nm features achieved with the EUVL tool at Sandia/Livermore: Archimedes star and bar patterns. The bar patterns in the right image provide an idea of the appearance of individual microtag cells. The bar pattern on the left demonstrates 150-nm features while the bar pattern on the right shows 100-nm features.

Conclusions

We have presented a concept for mass-producible microscopic computer-generated holograms. These microtags are mass-producible by means of advanced extreme-ultraviolet lithography (EUVL) techniques currently under development at Sandia National Laboratories in Livermore, California. The aimed-for 80- μm maximum dimension of the microtags renders them difficult to locate for the uninitiated. The 130-nm feature sizes make microtags very difficult to forge, at least for some time to come. Microtags do not require multiple masks to achieve multiple phase levels due to the off-normal-incidence read-out angle. A natural application involves the inclusion of microtags on integrated circuits for tracking and security purposes. Other applications include the tagging of credit cards and currency.

We are now in the process of laying out the masks for the microtags shown in Figs. 4 and 5. Future work will determine the optimal number of cells per microtag. This optimum will be defined by the nature of the encoded information (alphanumeric characters, binary codes, etc.). We are interested in minimizing the number of cells and introducing amplitude variation among the cells to compensate. Finally, the effects of physical damage to microtags will be modeled and experimentally verified.

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