

## CGH fabrication techniques and facilities

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### ABSTRACT

Computer-generated holograms (CGHs) are used in a number of important optical technology application areas such as holographic optical elements, optical processing and computing, optical testing, image and information display, beam forming, and beam scanning. Many different CGH fabrication devices (e.g., laser beam scanners, electron beam writers) and facilities have been developed and are in use. However, none of these devices ideally suit the requirements (e.g., resolution, space-bandwidth product, recording material) of many CGH applications. Furthermore, the access of many researchers to these facilities is limited and the technical support available is often poor. New facilities specifically designed for CGH fabrication would better serve the needs of the CGH research and development community. The requirements for a successful CGH fabrication facility including appropriate technical support for users are established.

### 1. INTRODUCTION

The possibility of a national facility for the fabrication of computer-generated holograms (CGHs) has been considered for the past decade. Some of the possible benefits of a national CGH facility are: (1) it would fabricate high quality CGHs for use by the research, development, and manufacturing communities, (2) it would avoid further expensive, needless duplication of facilities, (3) it would speed the development and application of diffractive optics techniques and devices, and (4) it would improve system performance in several important application areas (e.g., holographic optical elements, optical interconnect devices for high speed parallel processors, and invariant correlation filters for object detection and recognition).

Although many facilities are currently fabricating CGHs of various types, all of these facilities suffer from one or more of the following deficiencies: (1) performance limitations (e.g., resolution, space-bandwidth product, or recording speed), (2) cost, (3) CGH encoding or materials restrictions (e.g., restriction to binary amplitude or phase, or restriction to recording fringes), (4) data format inefficiencies, and (5) lack of technical support in CGH design and optics in general. Clearly, no existing facility can yet be considered to be acceptable as a national CGH fabrication facility.

This paper makes an effort to take the next step toward a better, and possibly national, CGH fabrication facility. A broad overview of CGH applications and technology is given in Section 2. CGH fabrication methods and devices are discussed in Section 3. Finally, in Section 4, the requirements which a successful CGH fabrication facility must meet are given and an in-depth study of user requirements is recommended.

### 2. REVIEW OF CGH TECHNOLOGY

The range of applications which can potentially take advantage of CGH is very wide. Some of the applications are shown in Figure 1. They have been grouped according to whether the CGH is used to modify only the phase of a wavefront or to modify both amplitude and phase.

CGH can be classified in many ways. Two possible methods are by material type and by type of diffraction effect utilized. The different types of CGH under each of these categories are shown in Figure 2.

## CGH APPLICATIONS

### Phase-only wavefront modification

#### Conventional optics

HOE - lens, mirrors, phase correctors

Testing of aspherics

Wavefront creation for COHOE fabrication

Scanners

Heads-up/helmet displays

#### Light redistribution

Beam intensity profile shaping

Data formatting - coordinate transformation

Digital data processor interconnects

Beam combiners, dividers

### Amplitude and phase wavefront modification

#### Displays

2-D, 3-D images

Sighting devices, reticles

Spatial filters for pattern recognition

Data memory, storage

Figure 1. The wide range of CGH applications.

## CGH CLASSIFICATION

### Material types

Amplitude-only

Continuous

Binary

Phase-only

Continuous

Binary

Amplitude and phase

### Diffraction effects

Scalar

Planar media and surface relief

Volume Bragg diffraction

Vector

Figure 2. Examples of CGH classification methods.

CGH can be copied in several ways. A contact copy can be made, usually for the purpose of transferring the CGH onto a new, more suitable material. Another possibility is the COHOE or Computer-Originated Holographic Optical Element. In this copying method, the wavefront reconstructed by the CGH is interfered with a second wavefront. For example, if this second wavefront is planar, then the effect is simply to copy the phase of the CGH while adding a high carrier frequency to achieve higher diffraction efficiency or a larger diffraction angle. Another example is for the second wavefront to be spherical and of high numerical aperture and the CGH wavefront to represent a desired phase correction; then the resulting COHOE can be a high numerical aperture aspheric. In the latter example, the space-bandwidth product required of the CGH is reduced by using a nonplanar wavefront generated by conventional optics.

Because of the wide range of applications in which CGHs may be used, there is also a wide range in the performance required of CGHs (see Figure 3). The specifications shown in the low range might apply to a CGH for a Fourier-transform-domain matched filter in a coherent optical correlator and those in the high range to an aspheric holographic combiner for a head-up display. For many applications, the required signal-to-noise ratio has not been adequately analyzed, hence the question marks in the table rather than numerical values. In addition, the diffraction angle required of a CGH can vary from zero to nearly 180° depending on the application. Although CGHs have been most commonly used in the wavelength region from the ultraviolet to the infrared, CGHs have also been made and used at x-ray and microwave wavelengths. It is neither expected or required that any one CGH fabrication device would meet all the specifications shown in Figure 3.

	Range	
	<u>Low</u>	<u>High</u>
Resolution	100 μm	0.05 μm
Space-bandwidth product	10 <sup>2</sup> x 10 <sup>2</sup>	10 <sup>6</sup> x 10 <sup>6</sup>
Size	(1 mm) <sup>2</sup>	(50 cm) <sup>2</sup>
Diffraction efficiency	<1%	~100%
Phase accuracy	λ	λ/50
Signal-to-noise ratio	?	?

Figure 3. The wide range of CGH specifications for different applications.

There are also a wide variety of methods for encoding the desired two-dimensional distribution of amplitude and phase in a CGH. The major encoding methods are shown in Figure 4. Each method has its own advantages and disadvantages. For the case of CGH used for two-dimensional image reconstruction, the inaccuracies inherent in most of these methods have been analyzed.

### MAJOR CGH ENCODING METHODS

- Amplitude and phase directly - ROACH
- Phase directly - Kinoform
  - Continuous
  - Binary
- Phase on carrier
  - Amplitude transmittance
    - Fringes
      - Continuous - Burch
      - Binary - Lee
    - Detour-phase
      - Continuous - Burckhardt and Lee
      - Binary - Lohmann
  - Phase transmittance
    - Phase versions of above

Figure 4. A classification of the major CGH encoding methods.

As has been the case in each CGH characteristic examined in this section, the range of CGH recording media is also very wide. Some of the principal types are listed in Figure 5. It is important to note that, even when the CGH can not be recorded in a material suitable for use in the application, it can usually be replicated in a suitable material. Not included in this list are the various real-time spatial light modulators that can be used to record CGHs. They are ordinarily restricted to uses in which the hologram must be recorded in near real-time, and are therefore not appropriate for a CGH facility. (They also typically have modest performance specifications).

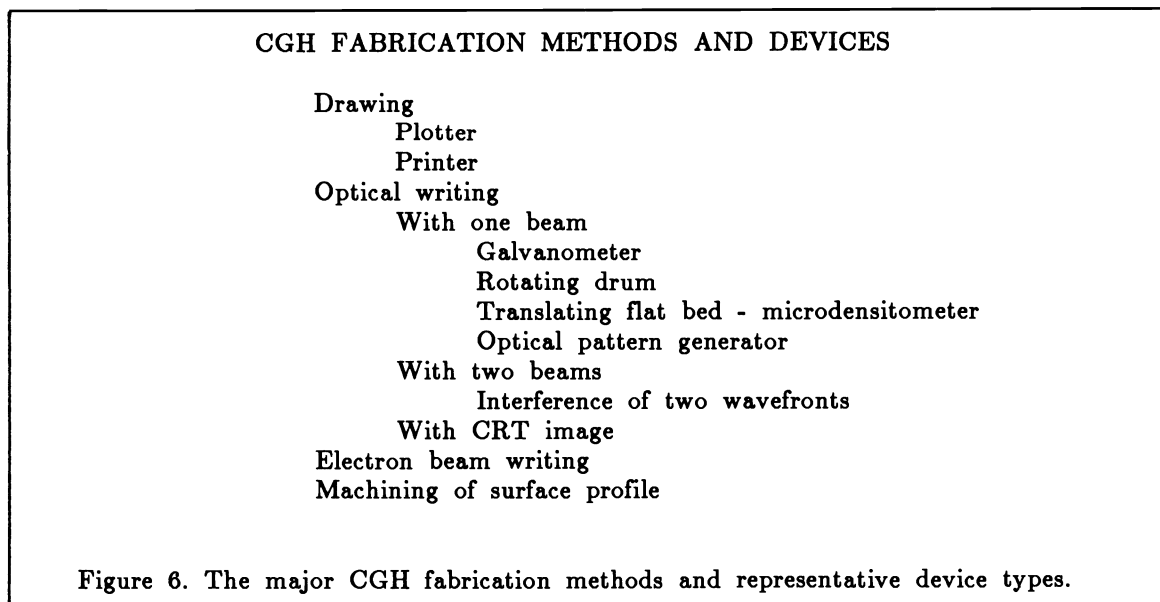
### CGH RECORDING MEDIA

- Photographic emulsions
  - Amplitude
  - Bleached
- Gelatin
  - Silver halide
  - Dichromated
- Photoresist, electron resist
- Photopolymers
- Multiemulsion - ROACH
- Machinable materials
  
- Replication materials
  - Above plus:
    - Glass, quartz
    - Si, GaAs, Ge
    - Metal

Figure 5. Examples of CGH recording and replication media.

### 3. CGH FABRICATION DEVICES

A large number of devices have been used to fabricate CGH. The principle methods and devices are listed in Figure 6. In addition to the categories listed in Figure 6, the devices can be divided into two classes: (1) those which were built for another purpose and were adapted for CGH fabrication and (2) those which have been designed and built specifically for CGH fabrication. Plotters, printers, rotating drum scanners, some translating flat bed scanners, optical pattern generators for microelectronic mask making, electron beam writers, and computer-controlled milling machines are members of the first class. Although useful CGH have been made with all these devices, better performance (e.g., smaller writing spot size, greater space-bandwidth product, more appropriate data formatting and CGH encoding) could be obtained if the device were redesigned specifically for CGH fabrication. Galvanometer scanners, devices which image a CRT to the recording medium, and devices which interfere two computer-controlled wavefronts belong to the second class. Although some of these devices are excellent for fabricating specific types of holograms, they all have performance limitations which make them unsuitable for fabricating a wide variety of CGH types.

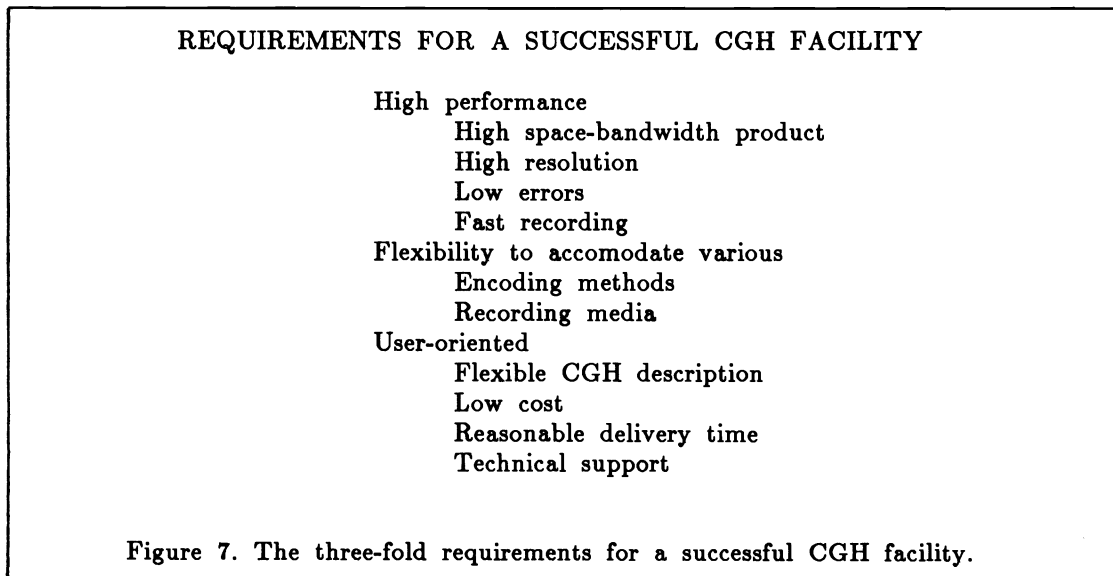


For example, consider devices which use a laser beam to write on a photosensitive film placed on a rotating drum. These devices have the advantages of (1) continuous modulation of the intensity of the laser beam allowing a continuous amplitude recording, (2) being relatively inexpensive to purchase and maintain, (3) fast recording speed, (4) potentially high space-bandwidth product, and (5) moderate resolution. Disadvantages are (1) positional inaccuracy can cause phase errors, (2) current use with photographic film produces a CGH with (a) phase errors due to thickness variations (correctable by mounting in an index matching fluid) and (b) low diffraction efficiency (correctable by copying onto a high efficiency phase material), and (3) restriction to a raster exposure pattern which is not optimum for writing CGH which consist of curved fringe patterns.

The currently popular electron beam recorder which is used for mask generation for microelectronics is another example. It has the advantages of (1) high (submicron) resolution, (2) high space-bandwidth product, and (3) allowing optics to build on microelectronics technology. However, current use of this device suffers from several disadvantages: (1) the recording is principally binary, (2) the devices and their maintenance are expensive, (3) recording speed is only moderate to low, and (4) much software development is need to allow easier user access, to permit efficient data formating, and to make use of the random-access ability to write curved CGH fringe patterns.

#### 4. CGH FACILITY REQUIREMENTS

The brief review of CGH applications and technology given in Section 2 indicates that multiple issues are involved in the choice of a CGH fabrication method and in the design of a CGH fabrication facility. As indicated by the examples of fabrication devices given in Section 3, all current facilities have some deficiencies. Designers and builders of future facilities should consider the CGH facility requirements summarized in Figure 7. First, the projected facility must offer high performance levels. High performance is not sufficient for success by itself, however. The facility must also have the flexibility to accommodate the various encoding methods and recording materials required by different applications. Finally, the facility hardware, software, and technical and management staff must be user-oriented. Only if all three of these requirements are met will it be asked to produce a sufficient volume of CGHs to justify the financial investment in a new CGH fabrication facility.



It is not possible at this time to determine which fabrication method (or methods), hardware, software, and support structure should be chosen for a new CGH fabrication facility. The CGH performance requirements of potential users are complex and require more study. When this has been accomplished, a trade-off study can be performed in an effort to select a CGH fabrication method and facility that best meets user community needs.

#### 5. ACKNOWLEDGEMENT

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