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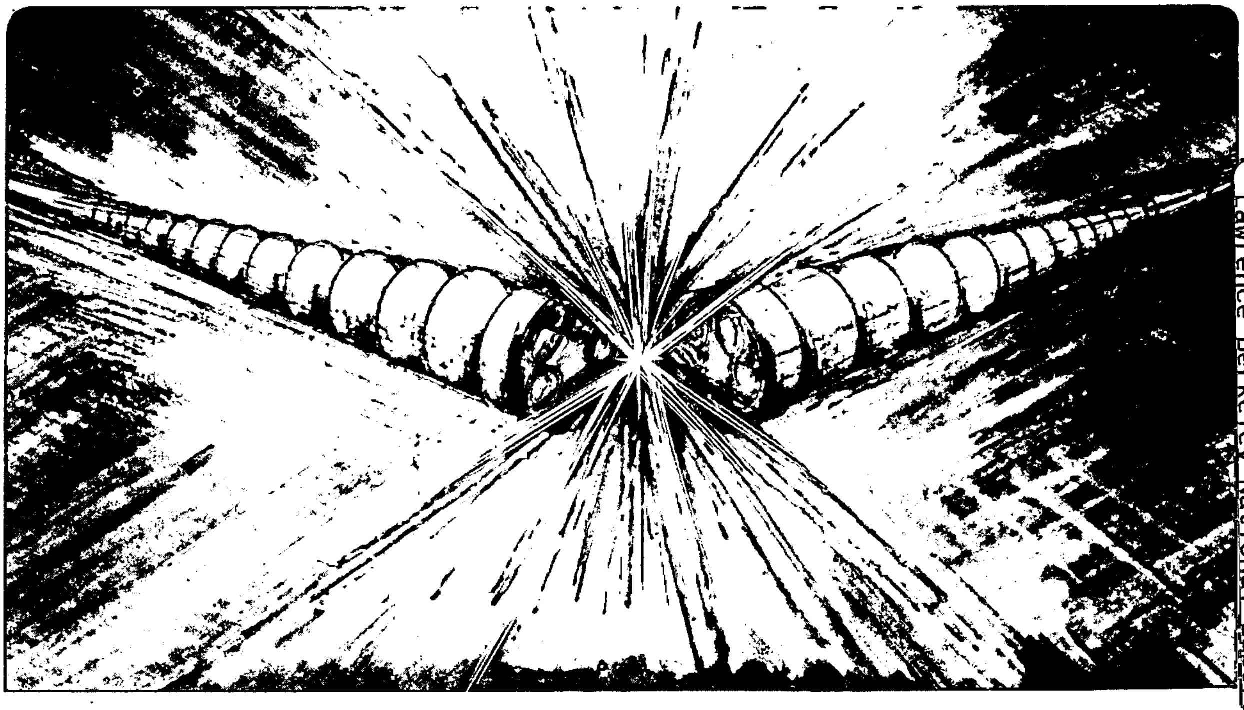

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POSSIBILITIES FOR PROJECTION X-RAY LITHOGRAPHY USING HOLOGRAPHIC OPTICAL ELEMENTS*

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INTRODUCTION

Although there is a considerable literature on proximity x-ray lithography [1], the interest in projection x-ray techniques has arisen fairly recently, mainly due to the efforts of the AT and T group [2]. The advantages of the projection approach seem to be the elimination of transmission masks and other problems of close proximity, the opportunity for demagnifying a mask of a coarser spatial scale, and, given a rigid, reflection mask, the possibility of cooling. The assumption behind the pursuit of these advantages is that the technical challenges of making the optical system that will perform the projection and the x-ray source that will illuminate it are tractable on some timescale. The optical fabrication tolerances and other design issues involved in carrying out projection using a conventional reflection system have been investigated by Rogers and Jewell [3]. These authors find that the needed tolerances are well beyond the present state of the art [4] even for spherical surfaces and the required surfaces in these schemes are aspheric. In this presentation we present an alternative approach to the process of projection which, of course, has its own, different challenges. It is a matter of one's judgement and technological starting point to decide which one of these (or other) approaches will provide the easiest path to a working x-ray projection lithography.

ADVANTAGES OF A HOLOGRAPHIC APPROACH TO PROJECTION

The following advantages can be adduced for the use of holographic methods in general:

1. The holographic image is aberration-free provided the hologram is illuminated by the reference beam that was used to form (or compute) it. This is exact within diffraction limits.
2. This means that one can achieve aberrationless imaging using only a single optical component, a computer generated hologram, and avoid altogether the use of imaging optics.
3. Only one optical surface is needed (good for stray light) and it is a flat (good for fabrication).
4. The above arguments do not require that the hologram be used at normal incidence and there are many advantages to using grazing incidence. (i) the power load of the x-ray beam is spread over a larger area, (ii) the use of multilayer coatings is avoided and (iii) the tolerances for surface figure and finish are relaxed compared to normal incidence. Furthermore the holographic geometry needs to be off-axis in order to avoid "twin-image" corruption of the projected image. Ordinarily such geometry requires a hologram recording resolution (in one direction) considerably greater than the image resolution [5]. The use of grazing incidence in that direction provides a way to avoid the special recording requirements.
5. The advantages of a rigid, coolable "mask" are applicable here, as in other projection methods.
6. The technology for making the hologram must, of course, be considered. The main advantage is that it is the same technology that one must necessarily be involved in for making masks; generally electron beam writing. The holograms are larger (see later) than the required image but the difficulty in terms of resolution and distortion is similar to that in mask making for proximity printing at the same feature size.

One must also consider the following disadvantages and challenges posed by this method:

1. The opportunity to fabricate a mask on a larger spatial scale and demagnify it is lost.
2. There are some questions which should be the subject of further study concerning unwanted signals due to the intermodulation term in the image and to higher diffracted orders. Both these tend to be negligible in normal x-ray holography because the samples are weak scatterers but here we would try to make the hologram with high diffraction efficiency. The twin-image is assumed to be eliminated by the use of off-axis geometry.
3. There is a need for a highly monochromatic, single-mode x-ray beam for illumination of the hologram. The value of $\lambda/\Delta\lambda$ needs to be on the order of the number of resolvable features

within the image width. Use of grazing incidence in positive diffracted order reduces the requirement somewhat but further study is needed to try to reduce it still further.

A NUMERICAL EXAMPLE

We consider now some specific design details based on Fig 1. Consider a feature size δ, wavelength λ, numerical aperture NA, hologram width L and image field width w. We then have $NA = \sin\beta = k\lambda/\delta$, where k is an empirical constant which we will take to be unity [6]. α is the grazing angle of incidence. α and β are thus to be chosen on resolution and reflectance grounds respectively. We are interested in the monochromaticity so we need to adopt a criterion for satisfactory imaging when temporal coherence is the limit. This issue has been investigated by Thieme [7] for the case of zone plates (the archetypal holographic optical element) from which we can say that satisfactory imaging is obtained if $\Delta\lambda/\lambda = 2/n$ where n is the number of *half period* zones. It follows that our criterion for satisfactory imaging is that the coherence length of the light must exactly equal the maximum path difference.

We must be careful not to set the image plane so that rays at angle β run from the hologram to the image plane top-to-top and bottom-to-bottom. This would result in the outer edge of the image plane receiving rays *only* at angle β thus only at one spatial frequency. This is obviously not enough to encode an image. We have therefore enlarged the hologram so that the outer point (D) receives frequencies (angles) from approximately half-maximum to maximum whilst the inner point (E) receives frequencies from zero to maximum.

From the geometry we find $w = L \sin(\alpha+\beta)/2$ and $p = BE = L \sin\alpha/\sin\beta$. The maximum path difference is for rays arriving at E and is $HBE\text{-}AE = BE\text{-}GE = (L \sin\alpha)^2/2p$. Setting this equal to the the coherence length we finally obtain

$$\lambda/\Delta\lambda = kw \sin\alpha/(\delta \sin(\alpha+\beta))$$

We now consider two cases based on reflective coatings made of carbon (safer from a contamination point of view) and gold (optimistically expecting theoretical reflectances). To get reasonable reflectance (60-80%) we set $\alpha = 0.125$ rad for carbon and $\alpha = 0.20$ rad for gold. Now choosing for example $\lambda = 100$ Å, $k = 1$, $\delta = 0.1$ µm, $w = 1$cm. we obtain

	α(°)	β (°)	L(cm)	p(cm)	$\lambda/\Delta\lambda$	beam width (cm)
Carbon	7.16	5.74	9.0	11.2	56,000	1.1
Gold	11.46	5.74	6.7	13.3	34,000	1.3

These are quite reasonable values except the $\lambda/\Delta\lambda$ values are rather challenging. Synchrotron-radiation, grazing-incidence monochromators have not yet demonstrated this level of performance. However, similar levels have been adopted as goals by the Advanced Light Source (ALS) group and resolution of 2.5×10^5 has been demonstrated [8] at 794 Å and 0.35×10^5 at 200 Å [9] using spectrographs. Since a lithography facility would probably work at *fixed wavelength* , one could imagine that it would not be too difficult to equal or even exceed the spectrograph values. With an undulator source one could easily make a diffraction-limited (i.e., adequate) resolution design. The problem would then, come down to grating fabrication tolerances. The problem of building this monochromator was part of the reason for considering 100 Å rather than a shorter wavelength.

REQUIRED HOLOGRAM WRITING RESOLUTION FOR A GIVEN IMAGE RESOLUTION

By means of the grating equation (including conical diffraction for the sagittal direction) we can obtain the writing resolution (fringe period) needed for 0.1 µm feature sizes (NA = 0.1). They are 0.57µm tangential and 0.10µm sagittal for carbon and 0.40µm tangential, 0.10µm sagittal for gold.

X-RAY SOURCES FOR HOLOGRAPHIC PROJECTION IMAGING

Contrary to the cases of direct projection imaging by an optical system or of proximity lithography, we require to operate a very high resolution monochromator. This will require an x-ray source of low emittance and high brightness. This means that the ideal synchrotron source would be about a 6cm-period undulator on a high-brightness storage ring like the ALS. Such a source would be essentially single-mode and should give exposure times on the order of a minute. Another interesting possibility is an x-ray laser. These devices already have the monochromaticity and although they do not yet have enough flux per mode at 100 Å to expose 1cm^2 of resist, one would expect that they probably would do on the timescale of a projection lithography program.

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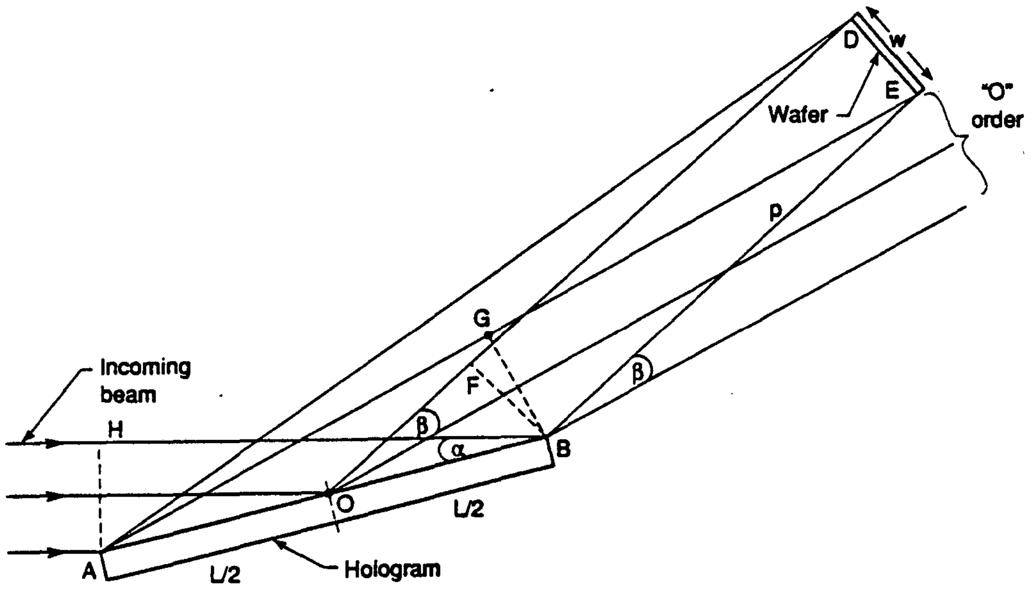

Figure 1

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