Introduction to ZPCI:

Sources of short wavelength radiation (x-rays, γ-rays, charged and/or neutral particles) not easily focused by conventional methods of reflection, refraction or diffraction can be imaged using two-step coded imaging techniques.[1,2] These techniques, in which an incoherent source casts simple, geometric shadows through an appropriately designed coded aperture, work well for both particle and photon emissions. The coded image, recorded by shadowcasting, must then be decoded by a numerical or optical method matched to the coded aperture design. The decoding step serves to reconstruct the original radiation source distribution. A particular coded imaging technique, zone plate coded imaging (ZPCI), involves the use of a Fresnel zone plate as the coded aperture, thereby allowing for the simple optical reconstruction of coded images. Figure 1 illustrates the principles of the two step zone plate coded imaging technique. An incoherent source distribution represented by three distinct emission points is considered. Each source point of short wavelength radiation (i.e. diffraction effects are negligible) casts its distinct shadow through a zone plate aperture onto a shadowgraph or coded image recording medium. Note that each zone plate shadow uniquely characterizes, by its size and position, the spatial location of its associated source point: an off-axis point casts an off-axis shadow, a distant point casts a small shadow, a close point casts a large shadow. Thus, the spatial distribution of the source is recorded in the distribution (position and size) of zone plate shadows in the coded image. All that remains is shadowgraph decoding (step 2), which because of the Fresnel zone plate geometry of the coded aperture may be achieved by simple optical methods reminiscent of holographic image reconstruction. The processed coded image is coherently illuminated using an optical laser. Each zone plate shadow focuses the incident laser light to a diffraction-limited spot, the image of its associated source point, thereby reconstructing the original source distribution point by point.

Coded imaging techniques have some unique capabilities which set them apart from conventional imaging methods. As mentioned above, coded methods are broadly achromatic working well for both particle and photon emissions. The only requirement on the source radiation is that its wavelength be sufficiently "short" that geometrical optics prevail during imaging encoding, and sufficiently "long" that appreciable attenuation occur in the opaque zones of the coded aperture. Another important advantage of a coded imaging method is its large radiation collection solid angle, typically four to six orders of magnitude greater than a pinhold camera of equivalent resolution. This can provide a significant S/N advantage for coded imaging of radiation sources of limited extent[3]. In addition, coded techniques have a tomographic capability. Three dimensional source detail is recorded and reconstructed as illustrated in Figure 1.

ZPCI Results:

Coded imaging techniques are for the first time being applied for the microscopy of short wavelength radiation sources.[4,5] This has been made possible by the emerging capability for precision fabrication of coded apertures on a microscopic scale[5]. In particular, the successful implementation of ZPCI for the microscopy of particle and x-ray sources has required the fabrication of micro-Fresnel zone plates of minimum zone width roughly equal to the desired resolution, material thickness greater than the radiation absorption length, and overall coded aperture size significantly greater than the size of the radiation source. UV lithographic techniques have been extended to produce free-standing, gold micro-Fresnel zone plates with linewidths (1-15 μm), thicknesses (2-38 μm) and diameters (0.4-15 mm).[7] These have been used to produce moderate resolution images of particle and x-ray emissions from laser-induced micro-implosions of deuterium-tritium filled glass microspheres of interest in laser fusion studies. Fig 2 shows such a ZPCI result. X-ray emission fropm a laser imploded microsphere is imaged with 8 μm resolution in four distinct energy channels showing the spectral evolution of emission detail in the directly illuminated spherical target surface as well as the compressed target core (produced by the ultimate implosion of the microsphere). These multi-spectral x-ray images were recorded on a single target shot with a single zone plate camera in which the coded aperture was a free-standing, gold Fresnel zone plate 5 mm in diameter, 16 μm thick with 5 μm minimum zone width. The coded x-ray images were recorded in a multi-layer filter-film pack, an arrangement which allowed the x-ray images in separate energy channels to be recorded simultaneously.

Fig 3 illustrates the particle imaging capability of ZPCI. In this experiment the 3.5 MeV alpha particle emission from the thermonuclear burn region of a laser imploded, D-T filled microsphere was imaged with 3 μm resolution. The coded aperture used was a 2 mm diameter, 5 μm thick free standing, gold zone plate with 5 μm minimum zone width. The coded alpha image was recorded in a thin cellulose nitrate film, a threshold-type ion track detector which served to record the alpha particle data while descriminating against background radiations of x-rays, electrons and protons.

Future Imaging Goals

There is strong motivation within a number of disciplines to extend ZPCI capabilities to higher energy x-rays (50-100 keV) and more penetrating charted particles (e.g. ~ 15 MeV protons) with little or no loss in image resoltuion. The prospect for such an extension depends almost exclusively on the development of techniques for the fabrication of high aspect-ratio (height/line width), gold Fresnel zone structures 50-200 μm thick. UV lithographic techniques with conventional photoresists are not easily extended to this regime of thick, high aspect ratio microstructures[7]. Even if all the processing details of thick structures could be worked out, diffraction effects would ultimately limit the sidewall verticality of such high aspect ratio zone plates. New fabrication techniques must be developed.

Fabrication of Thick Zone Plates:

We are using a dry etch technique, reactive ion etching (RIE), in oxygen to produce thick zone plate patterns in polymer films. We have used Dupont 2555 polyimide and a high purity, low viscosity epoxy, Spurr Low Viscosity Embedding Medium (SLVEM). The detailed procedure for thick, gold zone plate fabrication is outlined in Fig 4. A 0.5 mm thick glass substrate is successively coated with 200Å Cr (for adhesion) a (1000-5000Å) Au plating base, an additional 3000Å Cr layer (for plating base protection), a (50-200 μm) thick polymer layer polyimide or SLVEM, a (0.5-2.0 μm) Al layer (RIE mask material), and 1 μm of Shipley AZ 1350J photoresist (for pattern replication). The zone plate master pattern is transferred into the Al mask material by UV exposure and development of the photoresist and a wet chemical etch of the explosed Al. The resulting (0.5-2.0 μm) thick Al zone plate pattern on the polymer surface serves as a mask for the subsequent RIE of the polymer. The polymer is etched down to the 3000Å Cr layer, which serves to protect the Au plating base from being sputtering onto the polymer sidewalls. The Cr layer along with the remaining Al mask material are subsequently wet chemical etched, and gold is then electroplated within the etched polymer channels. A ring holder is attached to the outer diameter of the pattern and in successive order the remaining polymer, Au plating base, Cr adhension layer and glass support substrate are wet chemically etched leaving a free standing gold zone plate supported within an annular ring. Fig 5 shows a thick zone plate pattern in polyimide after step (4) of the fabricaton procedure outlined in Fig 4. The RIE parameters used were RF power density = 0.3 watt/cm^2; O_2 pressure = 10^{-2} torr; bias voltage = 525 volts. The pattern shown is 50 μm thick with a minimum zone width of 5 μm. The overall pattern diameter is 5mm. The thickest successfully etched pattern to date has been in SLVEM, 134 μm thick with a minimum zone width of 15 μm and an overall pattern diameter of 15mm. Shown in Fig 6 is a completed thick Fresnel zone plate structure in electroplated gold. The zone plate shown is 65 μm thick gold with 15 μm minimum zone width and 15mm overall pattern diameter. There appear to be some local non-uniformities in the thickness of the electroplated gold. Such non-uniformities will be a problem only for radiations having significant transmission (~25%) through the nominally opaque zones. In extending RIE techniques to the regime of very thick microstructures (75-200 μm) interesting phenomena have been observed which apparently do not arise in the fabrication of thin structures. In particular we find for patterns greater than 75 μm high and aspect ratios greater than 5-10:1 (a precise parametric dependence on thickness and/or aspect ratio has not been determined) the local R.E rate is influened by the pattern geometry. This is presumably due to local field effects which alter the trajectories of incoming oxygen ions.

The physical manifestation of these phenomena are (i) a non-uniform 'break-through' of the RIE process to the base metal due to the slower etch rate in the narrow zone regions and (ii) sidewall taper of the high aspect ratio zone structures. The non-uniform 'break through' may result in base metal being sputtered onto the polymer sidewalls, thereby complicating the subsequent electroplating step. A 3000Å protective Cr layer between the polymer and Au plating base serves to eliminate the electroplating problems associated with uneven RIE 'break-through' to the metal. The problem of sidew·ll taper eventually leads to failure of the narrowest, high aspect zones as illustrated in Fig 7. These effects have been mitigated by enclosing the RIE sample within a mesh Faraday cage at the cathode potential.[8] The sample is, therefore, within a presumably field free region while still subjected to oxygen ions which are accelerated to and pass through the mesh cathode. This has served to extend the thickness (100-200 μm seem possible) and aspect ratio (~10:1) of thick polymer structures which can be successfully reactive ion etched, but has not entirely eliminated problems of non-uniform pattern etching. Presumably local charge build-up may still influence local etch rates. Such local field effects currently limit the thickness and aspect ratio which can be achieved by RIE methods.

Conclusions:

Coded imaging techniques, which are useful for imaging radiations not easily focussed (e.g. x-rays, charged and/or neutral particles), may now be extended to more highly penetrating radiations. RIE techniques have been used to fabricate thick, high aspect ratio structures (Fresnel zone plates in particular) for use as coded apertures. The thickest RIE polymer structure fabricated was 134 μm with an aspect ratio ~ 9:1. The thickest gold zone plate was 65 μm with an aspect ratio ~ 4:1. The physical effects currently limiting the thickness and aspect ratio which can be achieved by RIE methods is local field build-up leading to etch rate non-uniformities and sidewall taper.

References

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Figure Captions

Fig 1 Basic principles of the two step zone plate coded imaging (ZPCI) technique.

Step 1: A zone plate shadow camera views the radiation source, which casts its shadow through the Fresnel-zone-plate aperture onto a recording film. In this illustration each point within the source casts its own separate zone plate shadow into the recording film. Step 2: the processed shadowgraph transparency is illuminated with visible laser light. Each individual zone plate shadow focusses the incident laser light to a diffraction limited spot, thereby reconstructing the original source distribution point by point.

Fig 2 X-ray images of a laser imploded microsphere target recorded using the zone plate coded imaging technique. Image resolution is 8-10 μm. The laser fusion target was a teflon coated spherical glass shell ~ 180 μm O.D. filled with deuterium-tritium fuel. The target was irradiated from top and bottom by multi-terawatt laser beams to ultimately produce the hot, compressed full core noted at the center of the x-ray images. The multi-spectral x-ray images shown were recorded on a single target shot by a single zone plate camera. They provide valueable information about the physical processes affecting target compression in laser fusion experiments.

Fig 3 Application of the zone plate coded imaging technique to alpha particle imaging is illustrated. ZPCI was used to image the region of the thermonuclear burn within a laser imploded, D-T filled glass microsphere target. The 3.5 Mev alpha emission from the D-T fusion reactions was used. Image resolution is 3 μm.

Fig 4 Fabrication steps in the preparation of thick (50-200 μm) micro-Fresnel zone plates.

Fig 5 Thick zone plate pattern reactive ion etched in polyimide. The overall pattern diameter is 5 mm.

Fig 6 Thick gold Fresnel zone plate produced using the fabrication procedures of fig 4. Overall pattern diameter is 15 mm.

Fig 7 Sidewall taper which can lead to buckling of narrow, high aspect ratio polymer structures during RIE is illustrated. These effects apparently caused by local field non-uniformities within the narrow, deep channels can be mitigated but not entirely eliminated by enclosing the sample within a Faraday cage.

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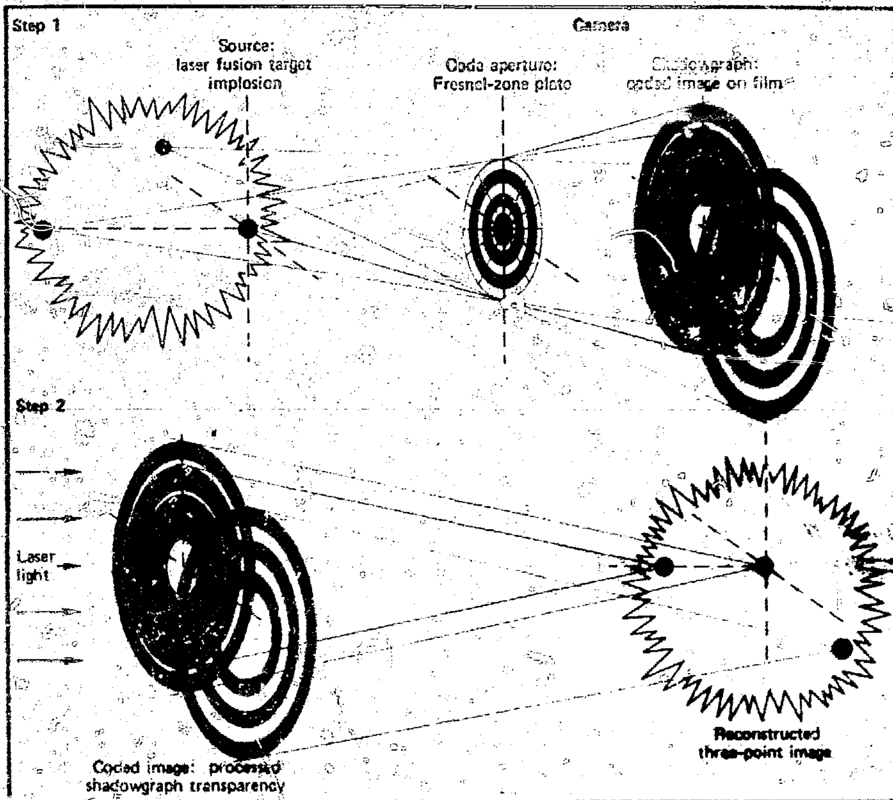
ZONE PLATE CODED IMAGING: PRINCIPLES



40-90-0578-1795

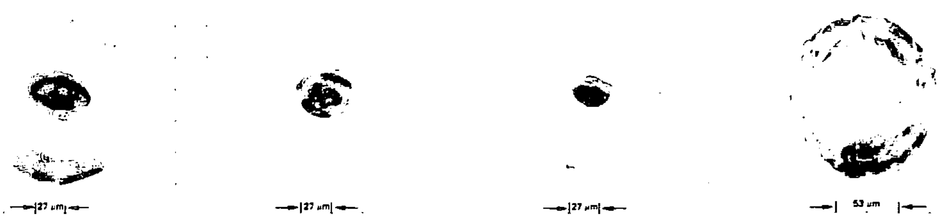
FIGURE 1

INTERMEDIATE DENSITY TARGET: MULTI-CHANNEL X-RAY IMAGES

The x-ray images shown are recorded:

- on a single target shot
- by a single zone plate camera

2.7 keV	4.6 keV	6.1 keV	16 keV (suprathermal)



Compressed core dimensions (FWHM)

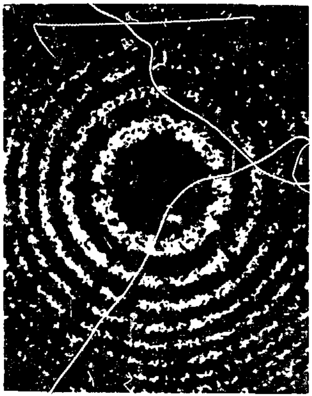
2.7 keV	4.6 keV	6.1 keV	16 keV (suprathermal)
31 X 65 μm	15 X 24 μm	12 X 22 μm	N/A

- Note the reduction in compressed core size as channel energy is increased

40-90-0979-2854

FIGURE 2

ZONE PLATE ALPHA IMAGING



Coded alpha image

88 μm

Laser irradiated target

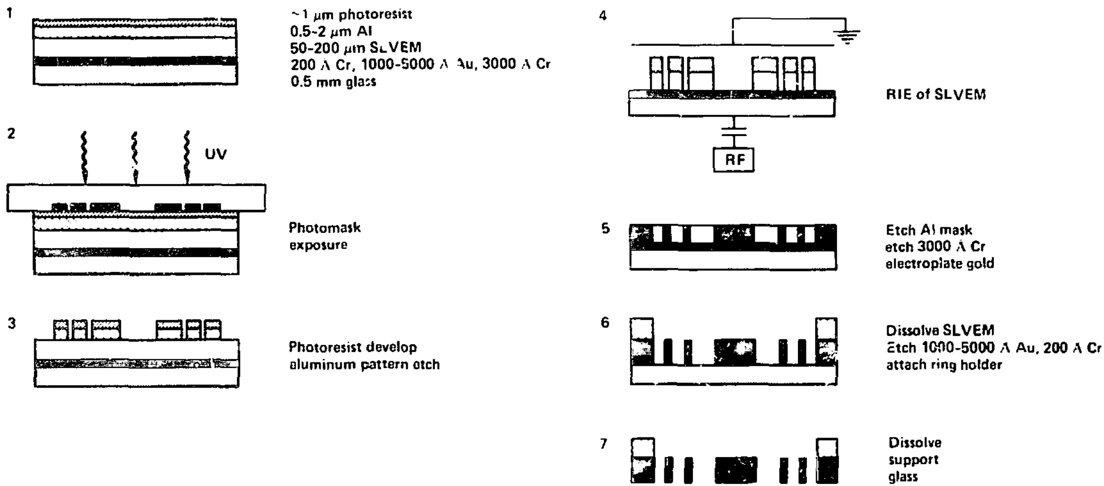
11 μm

Reconstructed image
(Isoemission contours)

40-90-0581-1239

FIGURE 3

FABRICATION OF THICK GOLD ZONE PLATES

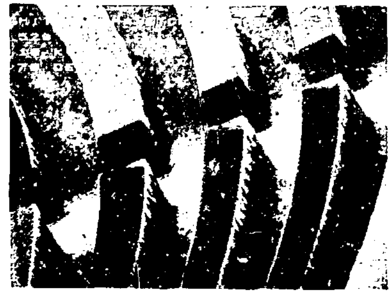


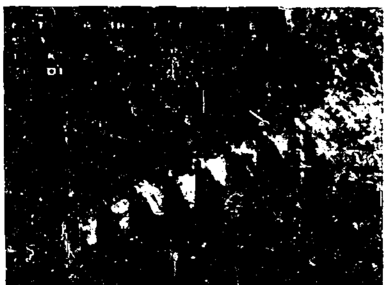
40-90-0581-1238

FIGURE 4

THICK ZONE PLATE PATTERN IN POLYIMIDE:

Reactive Ion Etch Techniques Produce High Aspect Ratio Zone Plate Patterns in Polyimide



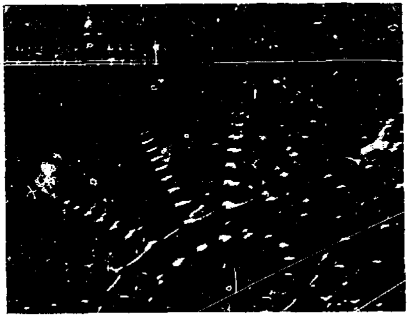


Zone plate pattern parameters:
Material: Polyimide
Aspect ratio: 10:1
Height: 50 μm
Minimum line width: 5 μm

40-90-1280-4551

FIGURE 5

THICK GOLD MICRO-FRESNEL ZONE PLATE



Zone plate parameters:

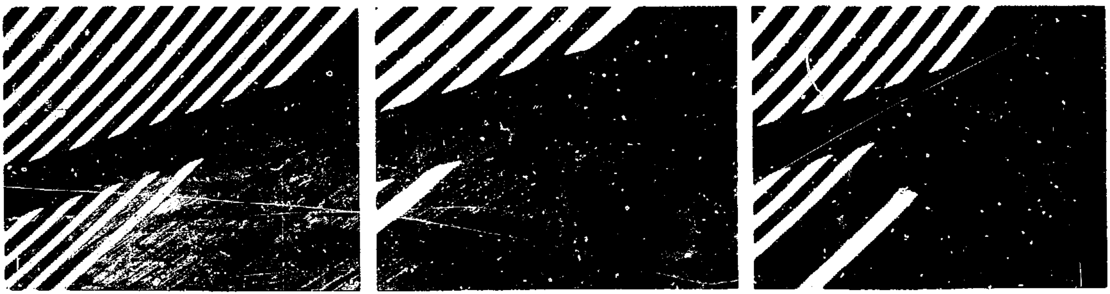
Thickness: 65 μm
Number of zones: 250
Min. zone width: 15 μm
Material: Electroplated gold

40-90-0581-1235

FIGURE 6

SIDEWALL TAPER EVOLUTION FOR HIGH ASPECT RATIO STRUCTURES

15 μm wide outer most zones buckle due to excessive sidewall taper



75 μm high | **85 μm high** | **90 μm high**

40-90-0851-1233

FIGURE 7