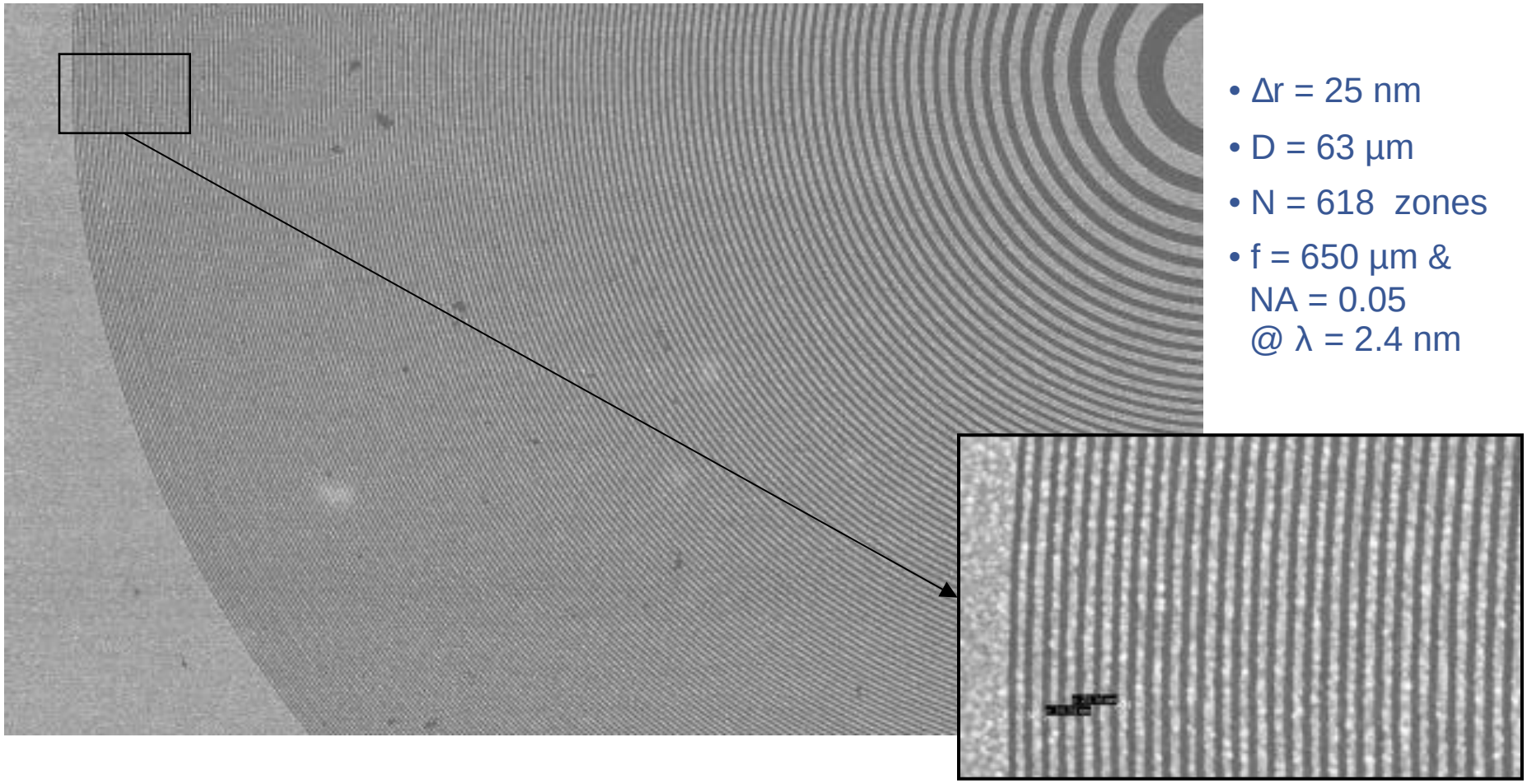
# SHARPER IMAGES BY FOCUSING SOFT X-RAYS WITH PHOTON SIEVES

By L. Kipp, M. Skibowski, R. L. Johnson, R. Berndt, R. Adelung, S. Harm, R. Seeman

Nature, **414,** 184-188 (Nov 8 2001)

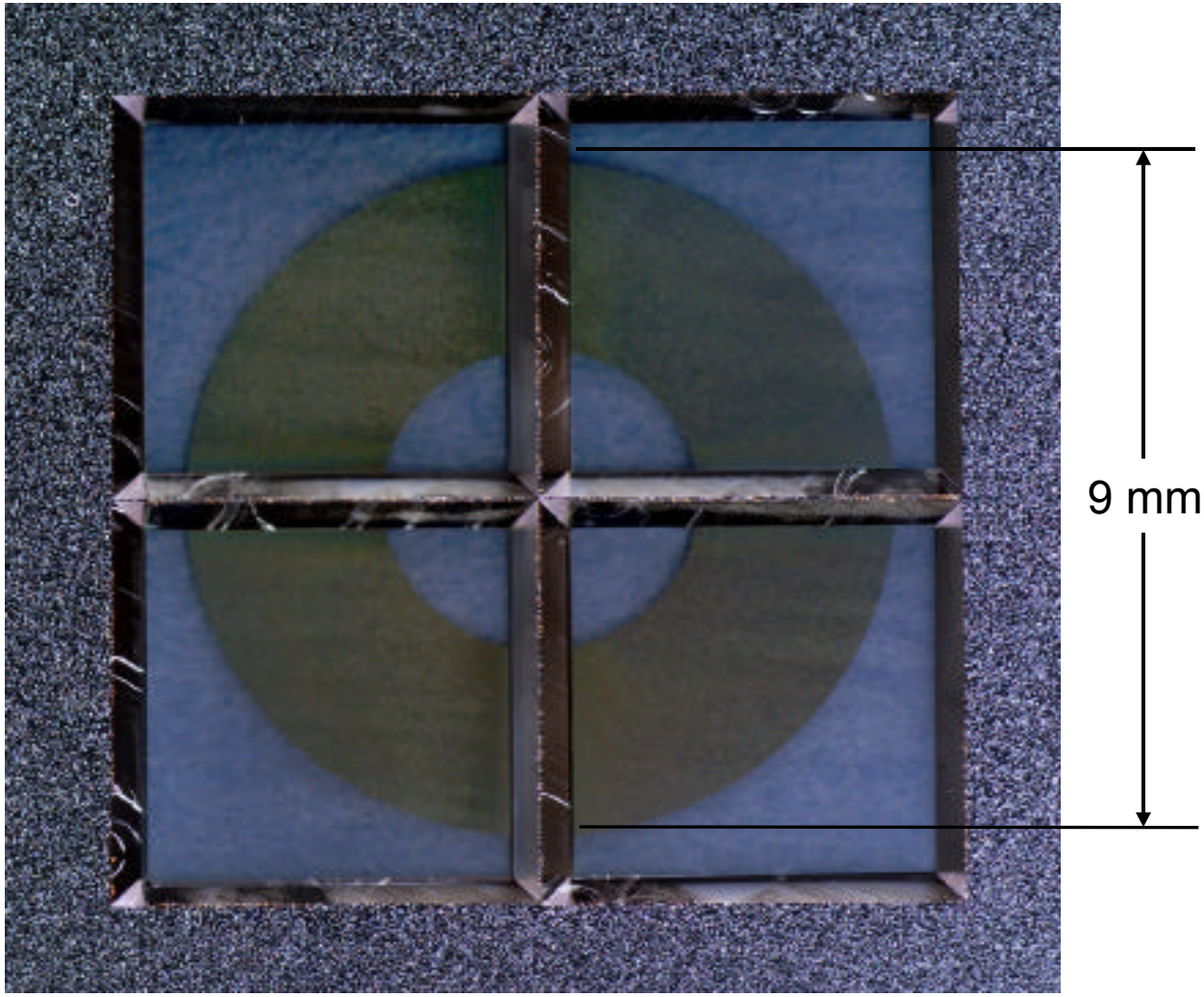
# New 25 nm Zone Plate

Erik Anderson, Deirdre Olynick and Bruce Harteneck, Zone Plate Fabrication with the Nanowriter.



- $\Delta r$ = 25 nm
- D = 63 µm
- N = 618 zones
- f = 650 µm & NA = 0.05 @ $\lambda$ = 2.4 nm

# New more efficient Condenser Zone Plate



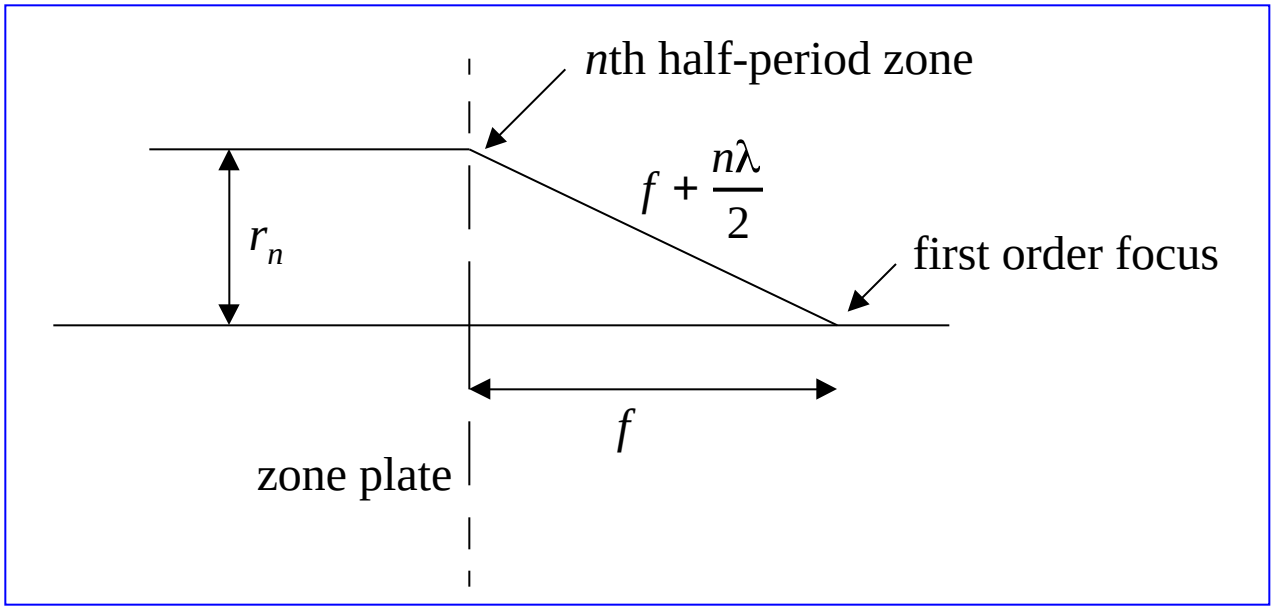

- $\Delta r$ = 55 nm
- D = 9 mm
- N = 41,000 zones
- f = 207 µm &
  NA = 0.43
  @ $\lambda$ = 2.4 nm

G. Denbeaux, L. Johnson, A. Lucero, W. Chao, E. Anderson, D. Attwood

# SUMMARY OF ZONE PLATES

**Fresnel zone plate:**

**Alternating open and opaque zones with square-wave geometry**




**First order focusing:**

$$\sqrt{r_n^2 + f^2} = f + \frac{n\lambda}{2}$$

$$f\left[1 + \frac{1}{2}\frac{r_n^2}{f^2} + \ldots\right] = f + \frac{n\lambda}{2}$$

$$r_n^2 = n\lambda f$$

**Diffraction-limited spot size:**

$$\text{Rayleigh res'n} = 1.22\,\Delta r_n$$
$$= 1.22\,w$$

**Efficiency in *m*th order:**

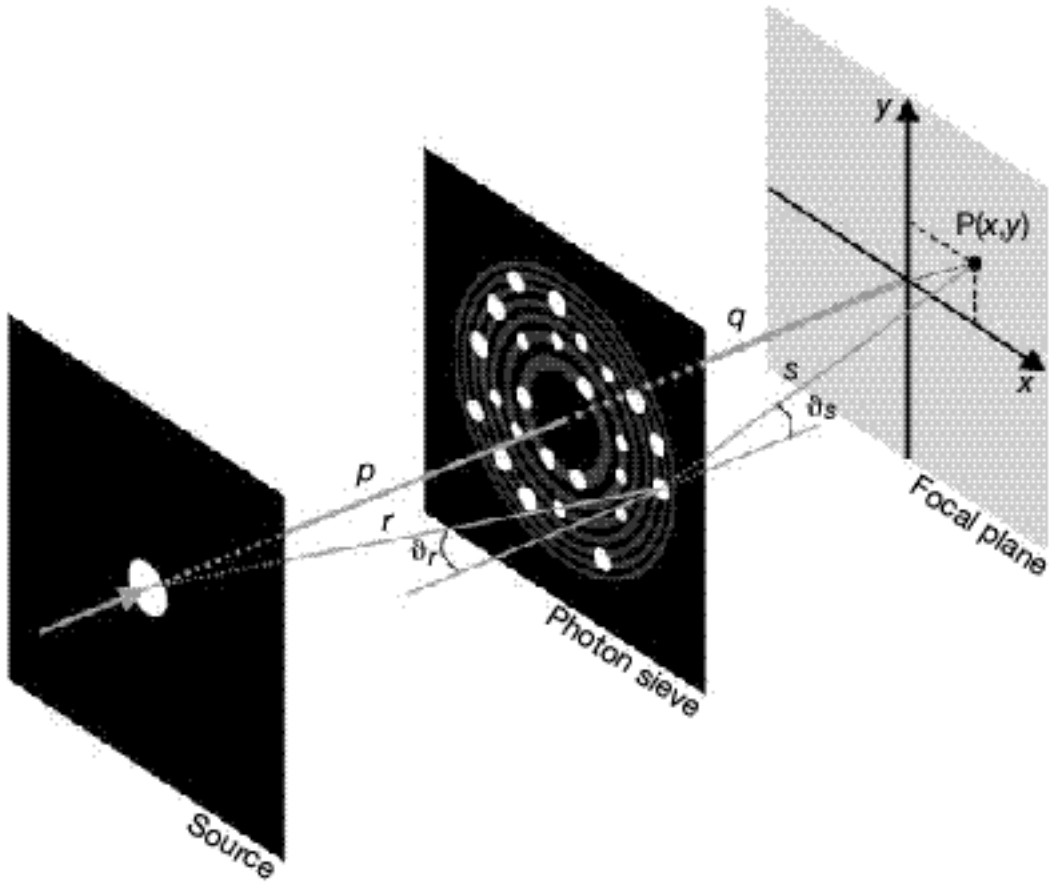
Fresnel zone plate: $\frac{1}{m^2\pi^2}$

Fresnel phase plate ($\Delta\phi = \pi$): $\frac{4}{m^2\pi^2}$

Ideal (parabolic) phase plate: 1

FZP zero order eff: 0.25, abs fraction: 0.5

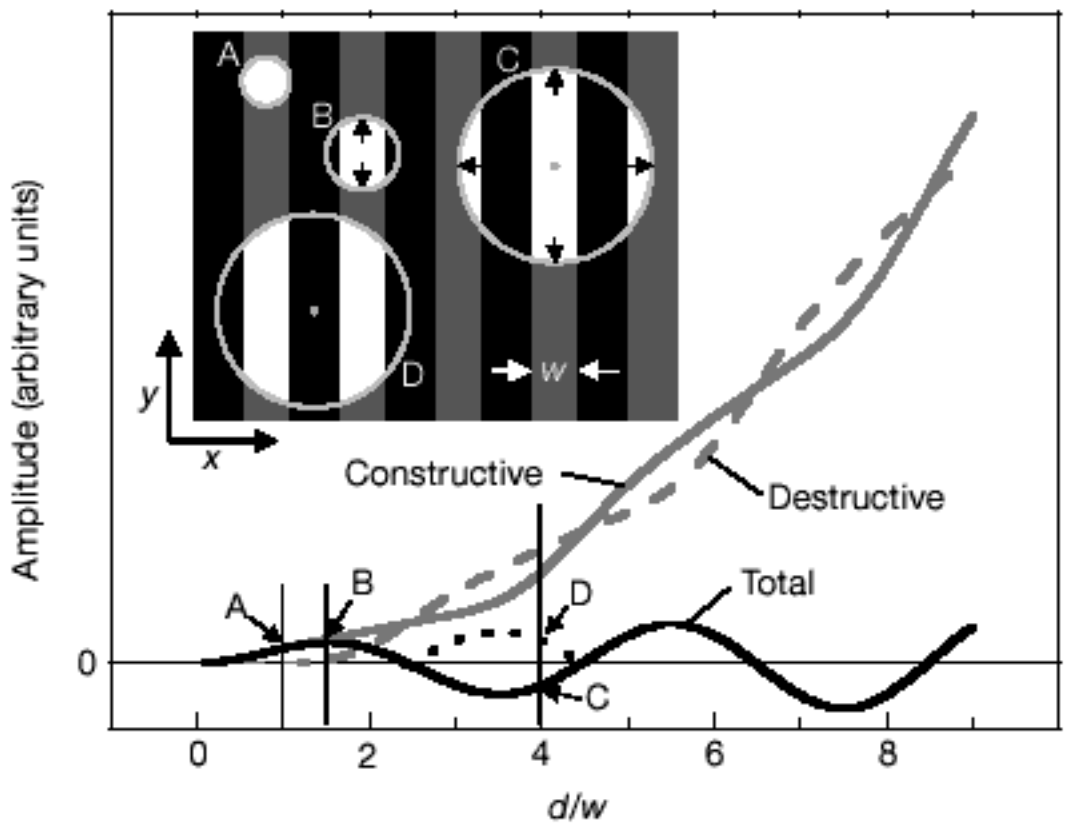
# PHOTON SIEVE: DEFINITION




$$\sqrt{r_n^2 + p^2} + \sqrt{r_n^2 + q^2} = p + q + n\lambda$$

- Focusing property defined in relation to underlying (mathematical) zone plate
- Outer zone width *w* of the underlying zone plate can be smaller than for practical zone plates
- Pinholes, of diameter *d*, are generally larger than *w*

# AMPLITUDE CONTRIBUTION AT THE FOCUS FOR VARIOUS PINHOLE SIZES




**Pinhole centered on a bright zone:**

- *d*=*w*
- *d*>*w*, local max of constructive contribution
- *d* larger, net contribution is destructive

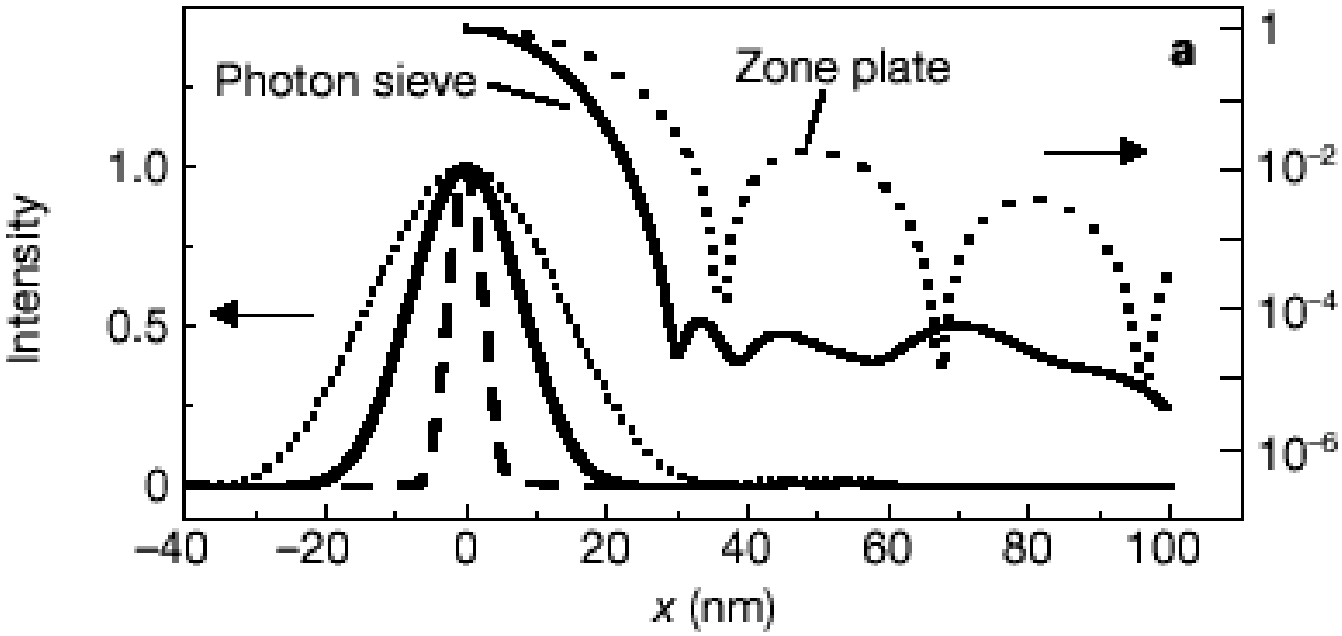
**Pinhole centered on a dark zone:**

*D.* *d* same size, net contribution is constructive

- Constructive contributions can occur for *R* = *d/w* equal to roughly 1.5, 3.5, 5.5 and 7.5

- Bright and positive = constructive
- Dark and negative = constructive

# RESOLUTION OF A PHOTON SIEVE COMPARED TO A ZONE PLATE




- Dotted line: zone plate
- Solid line: sieve with $R_{max}$ =2.4
- Dashed line sieve with $R_{max}$ =7.5
- Note that the spot size ($s$) of a sieve is that of the underlying zone plate so $s=d/R$ ($R$, $d$ single-valued)

**Results:**

| Device | $s$(nm) |
|---|---|
| Zone plate | 32 |
| Sieve $R_{max}$ =2.4 | 18 |
| Sieve $R_{max}$ =7.5 | 6 |

**Parameters:**

$w$ = 30 nm for the zone plate

$d_{min}$=30 nm for the photon sieve

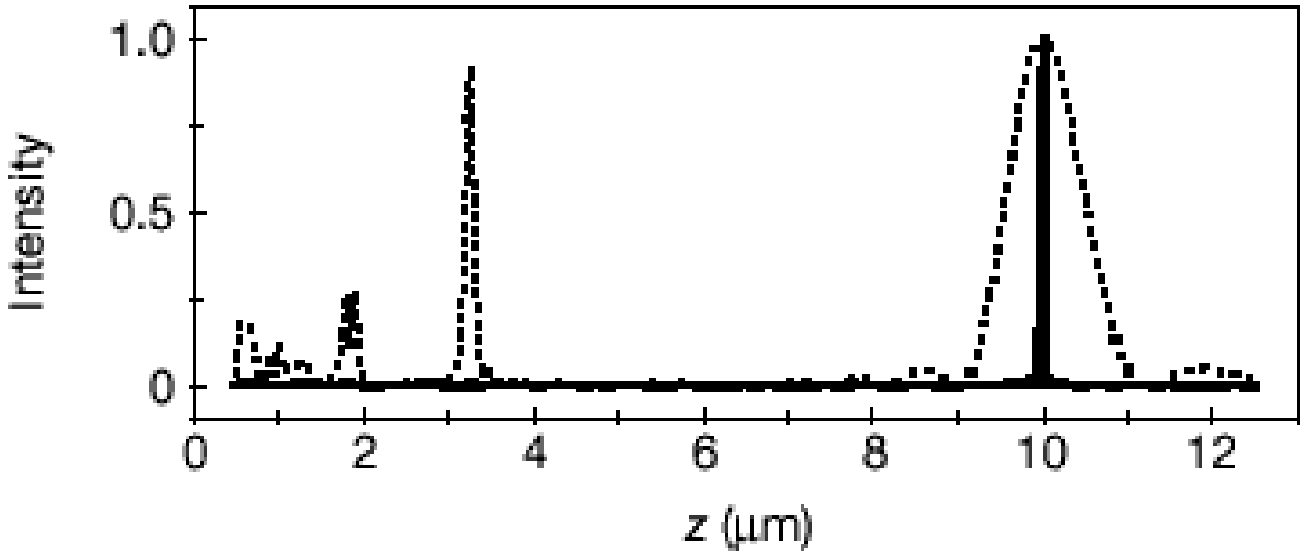
$\lambda$=2.4 nm

$p$=20 m

$q$=0.5 mm

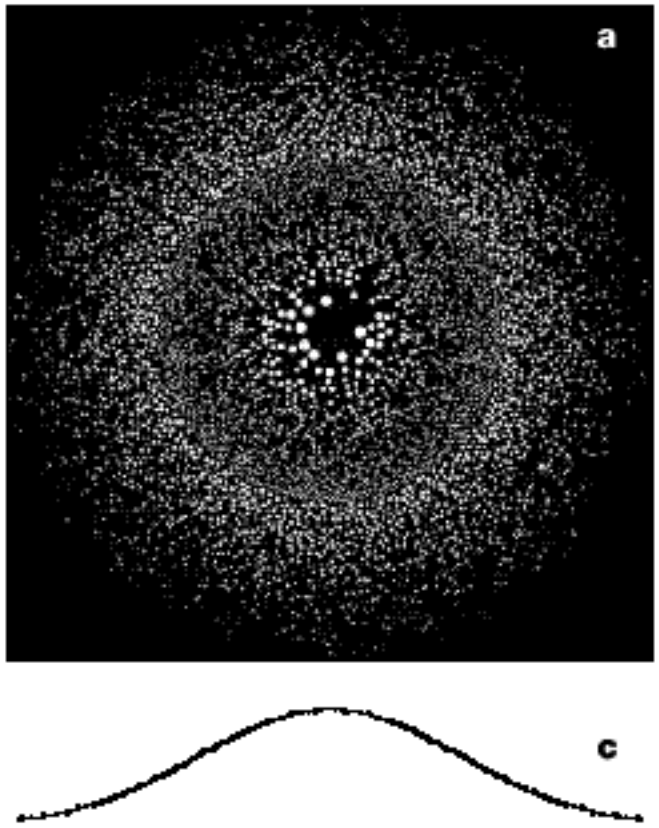
Sieves have $10^4$ pinholes and a window function apodized to suppress side lobes

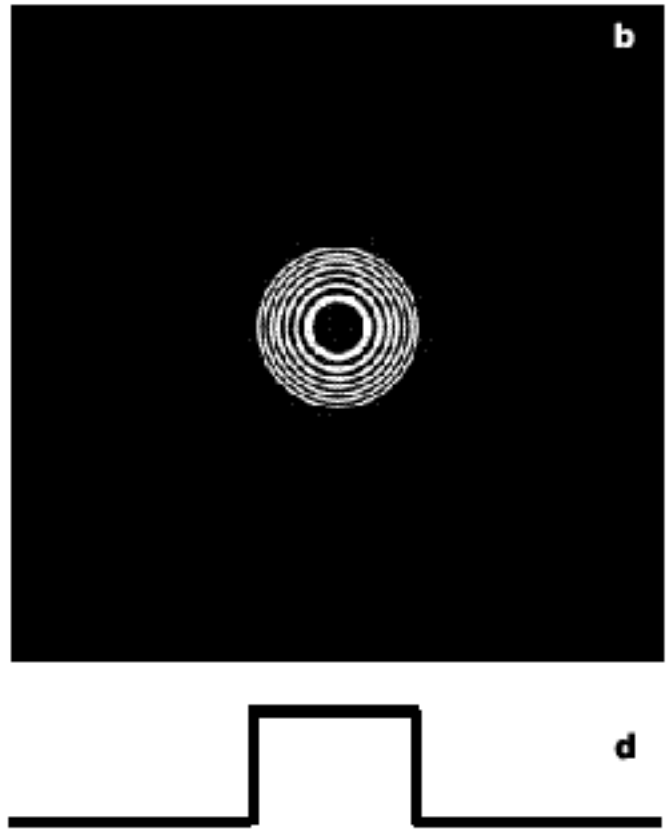
# SUPPRESSION OF HIGHER ORDERS




- Suppression is said to be by “The random distribution of pinholes on each zone”
- I think it works because the signs of the signals in figure 2 reverse three times more often in third order than in first - so a distribution that used only constructive parts of the “total” curve in first order would have both constructive and destructive parts in third  and would tend to average to zero

# MANUFACTURED SIEVE AND ZONE PLATE

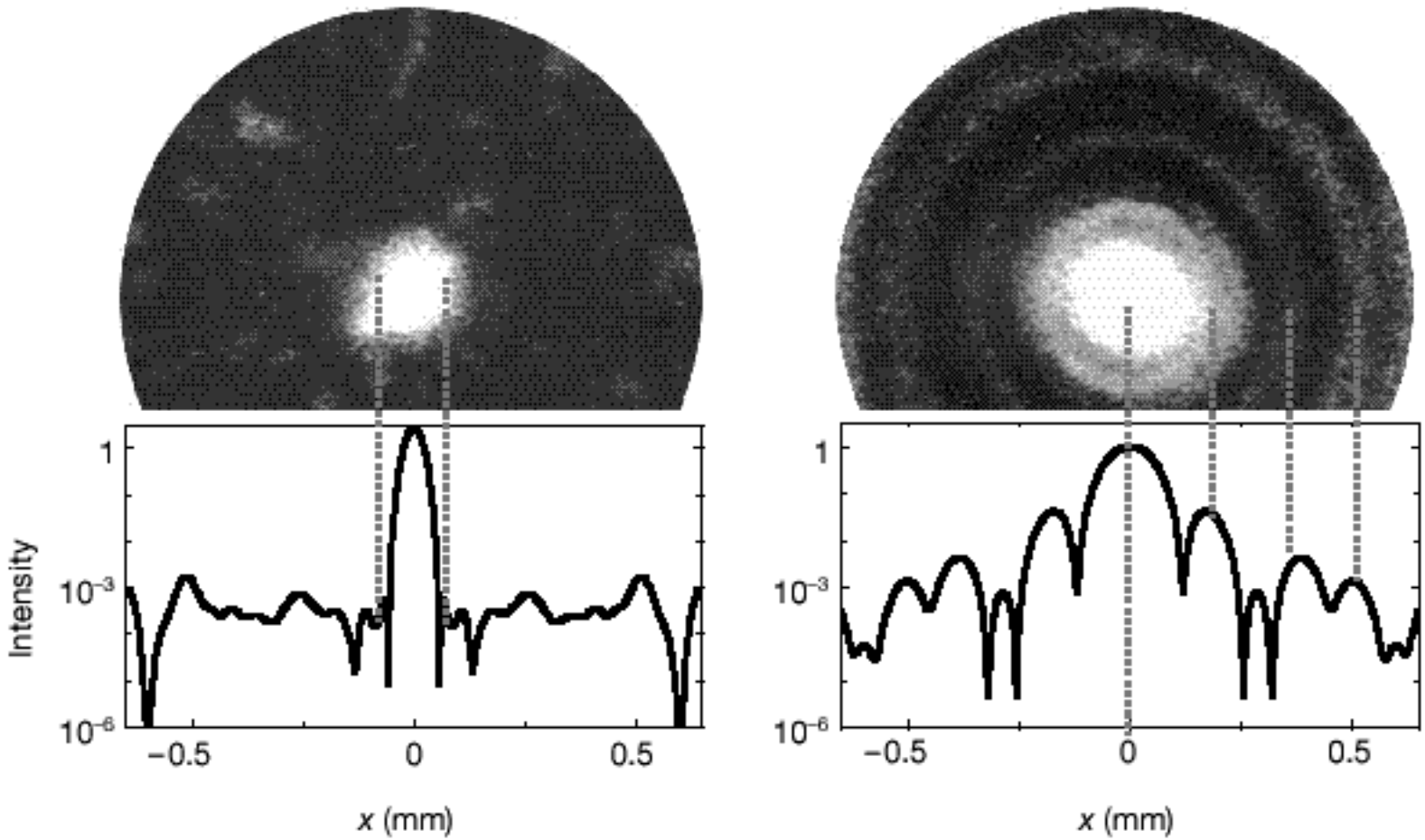



- Sieve with 5600 pinholes
- $d_{min}$ = 100 µm
- $R_{max}$=4

- Zone plate, $w$=100 µm
- Wavelength = 633 nm both cases

# VISIBLE-LIGHT EXPERIMENT




Results show good agreement with calculation. The narrower peak and good side-lobe suppression of the sieve is evident.

# ZONE PLATES FOR ELECTRONS MADE BY HOLE DRILLING

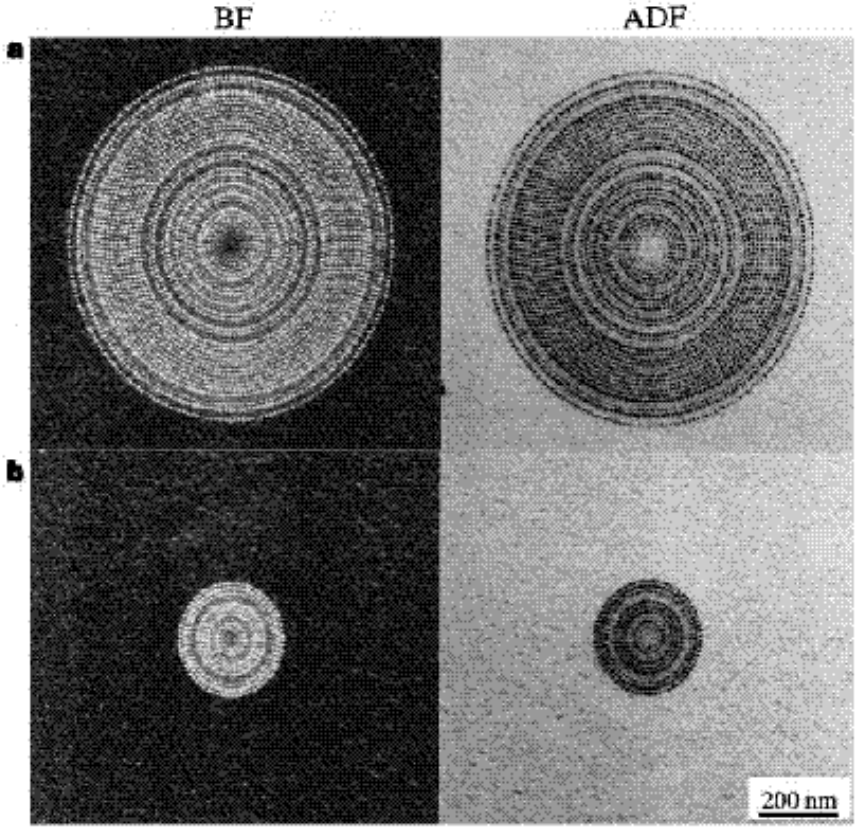



**Figure 2** Two Fresnel lenses with different focal lengths. Bright field (BF) and high angle annular dark field (ADF) images of nominal focal length of **a**, $f = 1$ mm and **b**, $f = 0.25$ mm lenses. The diameters of each lens are **a**, 700 nm and **b**, 236 nm. Before observation, the lenses were fabricated in VG HB501 STEM with a probe current of ~200 pA at 100 keV. An a-$AlF_3$ film, 68 nm thick, was overwritten 30 times with the lens pattern. The total fabrication time for the lenses was 60 s and 6 s for **a** and **b**, respectively. A single zone has the same width as the hole spacing from the 10th ($r_m = 316$ nm) and 3rd ($r_m = 112$ nm) zone outwards for **a** and **b**, respectively. The outer zones beyond half of the radius demonstrate this aliasing effect.

## Nanofabrication of solid-state Fresnel lenses for electron optics

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**Lenses for precision electron optics are mainly magnetic, requiring large cylinders of soft iron to focus an electron beam. Such lenses can only be convergent[1], and so suffer from spherical aberration. Electrostatic lenses are sometimes used, but tend to be even more cumbersome. The advent of high-brightness electron guns for scanning transmission electron microscopy has made it possible to use the resulting tightly focused electron beams to drill holes a few nanometres in size and of controlled depth in some inorganic thin films[2–5]: such patterned structures can then be used to manipulate the phase of an electron wave in a manner analogous to light optics[6,7]. Here we use this approach to fabricate compact solid-state 'pixelated' Fresnel lenses for electron optics. These lenses, which can be convergent or divergent, are not expected to compete with conventional magnetic lenses in most applications (such as microscopy), but may find a niche in electron-beam lithography.**

Nature, **394**, 49-52 (1998)

# DIFFERENT RULES FOR VOLUME GRATINGS

1200 OPTICS LETTERS / Vol. 26, No. 15 / August 1, 2001

## Efficient high-order diffraction of extreme-ultraviolet light and soft x-rays by nanostructured volume gratings

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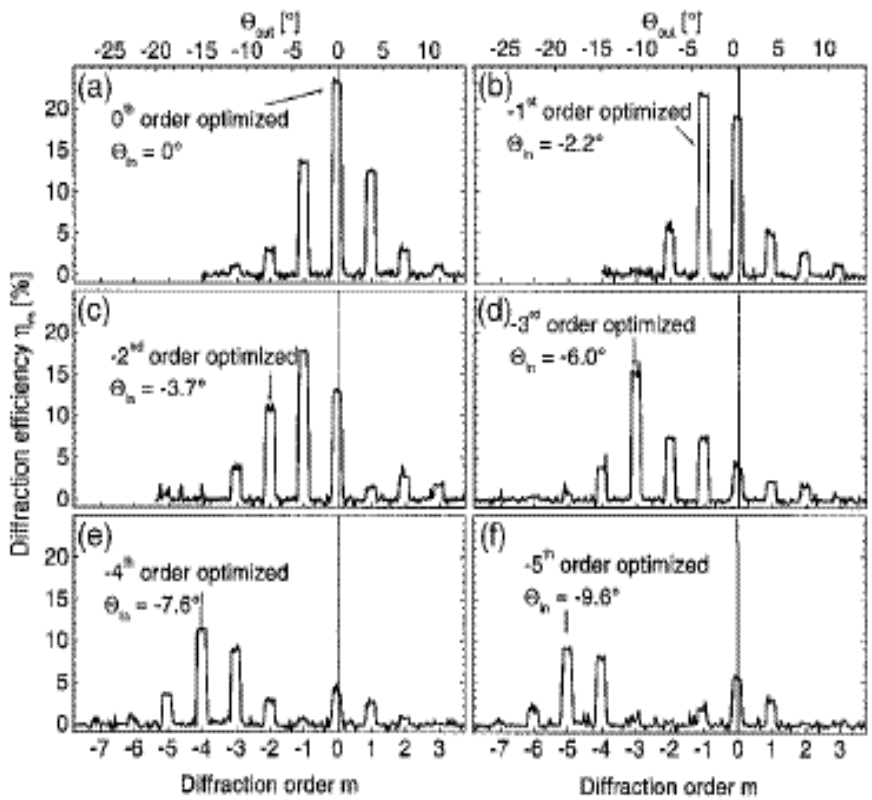


Fig. 3. Measured diffraction spectra of a copolymer grating with $\Lambda = 200$ nm and $t \approx 700$ nm at 13-nm wavelength. We chose the angle of incidence $\Theta$ to maximize the respective order of diffraction. The observed diffraction patterns match the theoretical spectra shown in Fig. 2.

- Efficiency does not fall off like $1/m^2$
- Efficiency can be high in high order
- Is governed by Bragg-type reflection law

## DISCUSSION: COMPARISON WITH ZONE PLATES

| PROS | CONS |
|---|---|
| Orders higher than 1 are well-suppressed (-1 and zero are expected to be present at the same strength as a FZP) | Pinholes must mimic an exactly round hole in a planar (thin) opaque sheet |
| Side lobes suppressed conveniently | • Round (at least symmetrical)<br>• Parallel to axis |
| With 2 nm positioning a 6 nm outer zone can be used implying 6 nm resolution with $R$=5.5 and 33 nm pinholes | • Smooth straight inner surface and constant depth giving no unintended phase distortions |
| Aberrations can be corrected conveniently | Poor flux: about a factor ten down compared to a zone plate of equal area |

# CRITICISMS OF THE PAPER

- Poor treatment of intensity which is a key weak point of a sieve device, no mention of zero or negative order
- Wrong use of the term order in my view
- No acknowledgement of volume zone plates (Schneider et al)
- No acknowledgement of similar work in electron imaging
- The probability distributions of the hole size and position were clearly known but were not divulged
- Missed opportunity: any sieve could be implemented as a *phase* sieve with similar gain in efficiency to zone plates