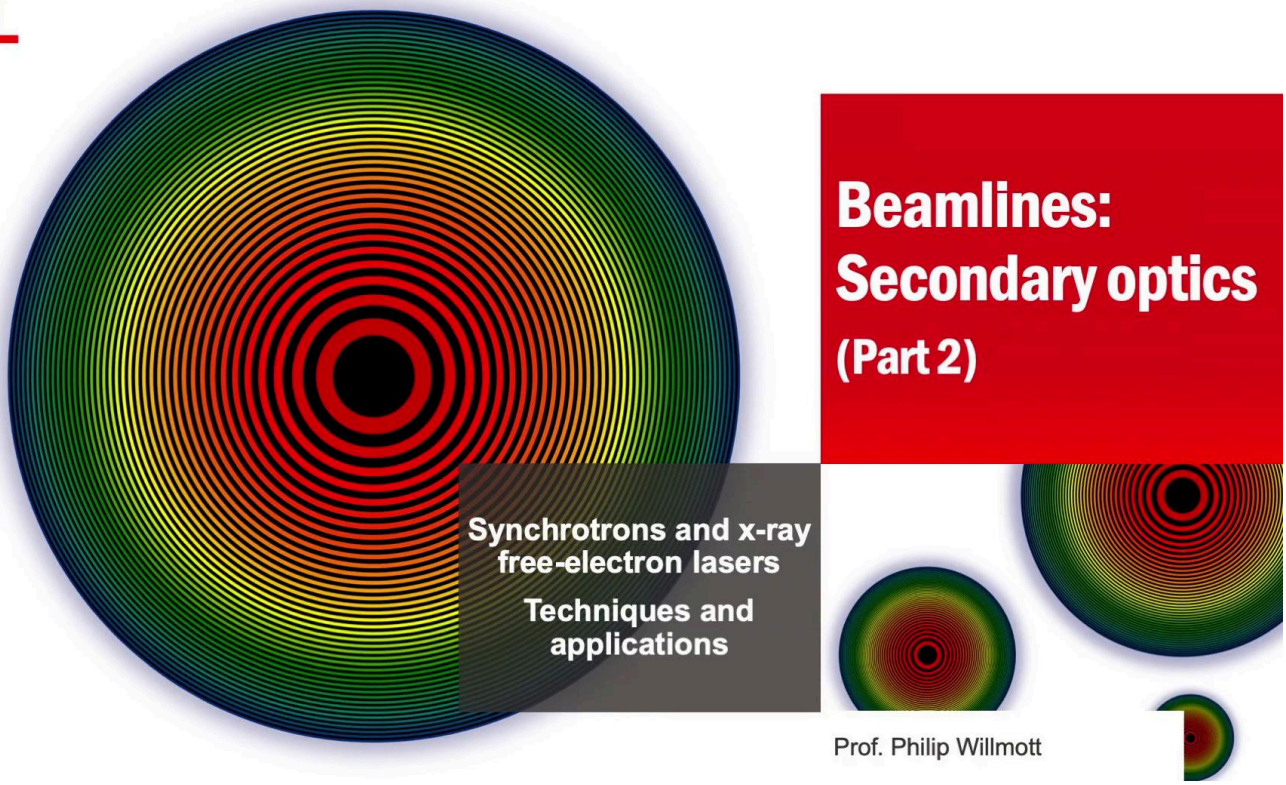
EPFL

Beamlines: Secondary optics (Part 2)

Synchrotrons and x-ray free-electron lasers

Techniques and applications



Search MOOC

Video

EPFL

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Contents and objectives of this video

- Fresnel zone plates
  - Absorption type
  - Phase type

Welcome back. In this video, we take a closer look at the microfocusing lens called the Fresnel zone plate, or FZP. Traditionally, these are based on structures consisting of alternating absorbing and transparent rings, but more recently, so-called phase zone plates, or PZPs, have been developed, in which the entire structure is transparent.

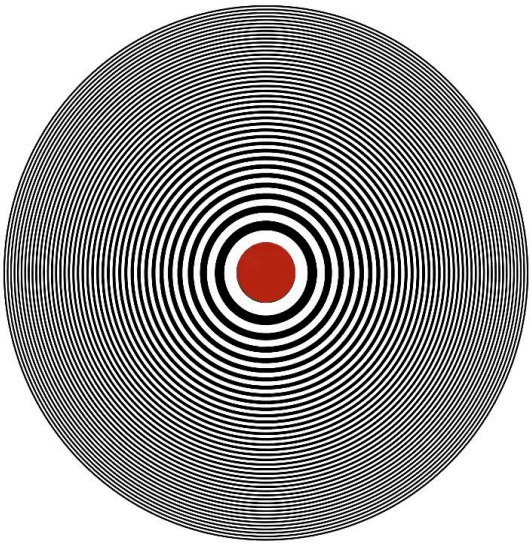
Notes

Summary

0m 05s

Fresnel zone plates

- Set of concentric rings “Fresnel zones”
  - Either
    - Transparent/opaque
    - Phase advance $\pi/0$ (“Phase zone plate”)
  - Each ring has equal area = $\pi\lambda f$
- Based on diffraction
  - Interference between radiation emerging from each ring



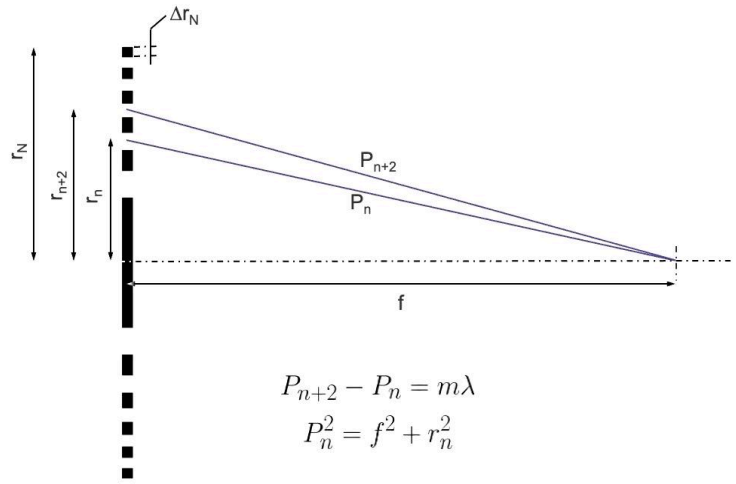
FZPs are made from a set of alternating opaque and transparent concentric rings, or, in the case of phase zone plates, concentric rings of thinner and thicker material, but both being transparent. Historically, Fresnel zone plates were developed for soft X rays, but as fabrication techniques have advanced, they are used increasingly in the hard X-ray regime. The inner and outer radius of each ring is determined by the condition that their areas are all equal, and equal to Pi Lambda F. If we take typical values for a hard X-ray, Fresnel zone plate of F equals 100 in millimetres, Lambda equals two angstroms, we obtain an area of 6.28 times 10 to the minus 11 square metres. This would mean that the central disc has a radius of 4.5 microns and a disc containing 1000 rings would have an outer radius of 140 microns. This is just perfect for capturing a modestly focused primary X-ray beam from an undulator beamline. But how do FZPs work? Focusing is based on diffraction. More precisely, positive interference between radiation passing through each ring at the desired focal length. So let's look at this now a bit more closely.

Notes

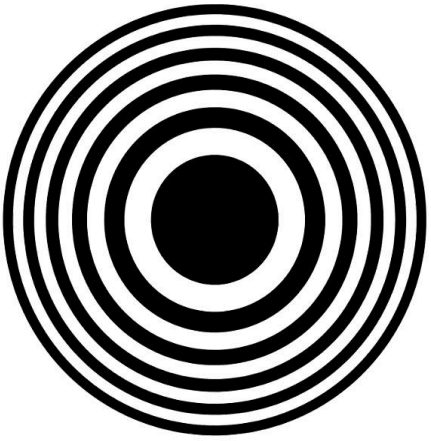
Summary

0m 34s

Fresnel zone plates



$$P_{n+2} - P_n = m\lambda$$
$$P_n^2 = f^2 + r_n^2$$



See also: Section 5.5.3 of Intro to Synchrotron Radiation, PRW, or http://zoneplate.lbl.gov/theory

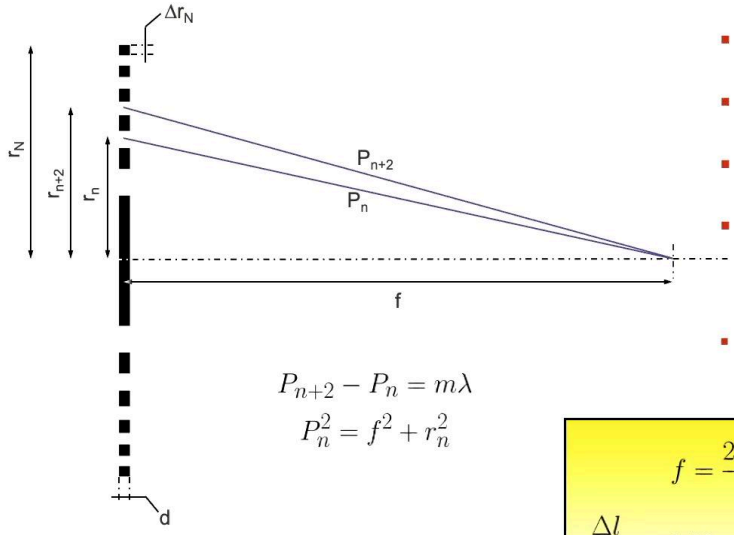
Consider here the profile of a Fresnel zone plate. The important parameters here are the radius of the Nth rign, denoted RN, and that of its next transparent neighbour with radius RN plus two. The outermost ring has a radius R big N, and width Delta R big N. Lastly, the focal length is labelled F. Consider now the optical paths taken from the transparent Nth ring labelled PN, and from the N plus two ring labelled PN plus two, to the focal spotter F. For this spot to be the focus, we require that the optical path difference PN plus two minus PN be an integer multiple of the wavelength's Lambda. From Pythagoras, we can also state that PN squared equals F squared plus RN squared.

Notes

Summary

2m 09s

Fresnel zone plates – example



- Goal: f = 100 mm, Δl = 50 nm, λ = 2 Å
- Δr_N = 61 nm
- r_N = 164 μm
- N = 1344
- r_1 = 4.47 μm

$$P_{n+2} - P_n = m\lambda$$
$$P_n^2 = f^2 + r_n^2$$

- N.B. d_{Au} > 4 μm for > 95% absorption
  - $d_{Au}/\Delta r_N$ > 66

$$f = \frac{2r_N \Delta r_N}{\lambda} \qquad r_n \approx \sqrt{n\lambda f}$$
$$\frac{\Delta l}{\Delta r_N} = 1.22 \qquad \mathrm{NA} = \frac{\lambda}{2\Delta r_N} \qquad \Delta r_N = \frac{1}{2}\sqrt{\frac{\lambda f}{N}} = \frac{\lambda f}{2r_N}$$

See also: Section 5.5.3 of Intro to Synchrotron Radiation, PRW, or http://zoneplate.lbl.gov/theory

Using these boundary conditions, and looking at the first order diffraction condition, by which I mean M equals one, it emerges that the focal length F equals two RN Delta RN divided by Lambda and R little N is approximately equal to root N Lambda F. The derivation of both these expressions and all subsequent ones in this video is provided in Section 5.5.3 of my introductory book on synchrotron radiation, or, alternatively, at the website from the Lawrence Berkeley Laboratories, also given here. An important relationship is the ratio between the ultimate focal spot size of the Fresnel zone plate and the width of the outer ring, which is 1.22. Let us take an example for hard X-rays with two angstrom wavelength, or a photon energy of 6.2 kV and an FZP, which has a focal length of 100 millimetres and can resolve features down to 50 nanometres. This sets an outer ring with width Delta R big N of 61 nanometres and radius RN equals 164 microns. There are 1,344 rings, and the inner disc has a radius of 4.47 microns. Note also, that for the absorbing rings to efficiently absorb the two angstrom radiation, they need to be more than four microns thick if one uses gold as the absorbing material. The ratio of this to the outer ring width is 66 or more, which is quite a technological feat.

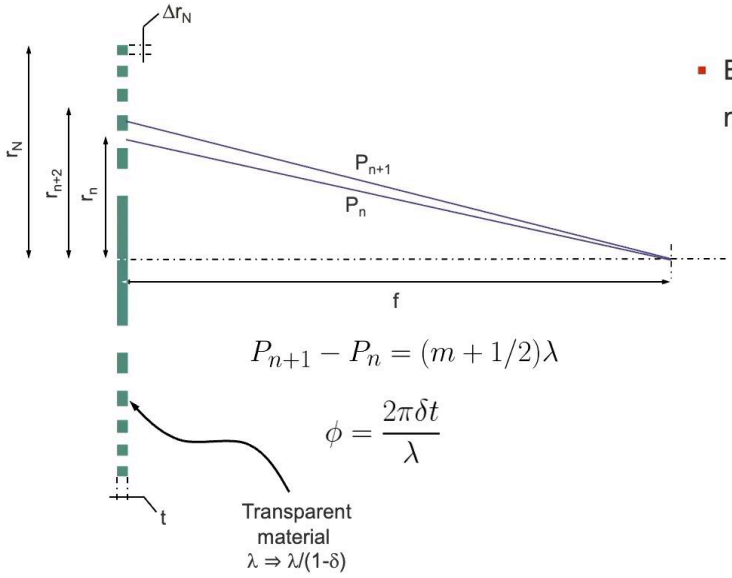
Notes

Summary

3m 19s

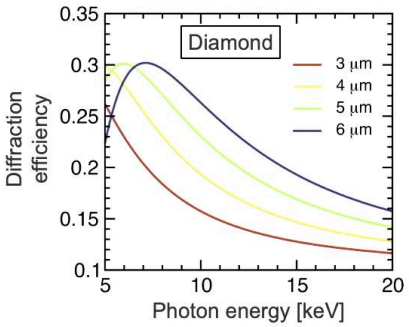
Phase zone plates

- Opaque rings
  - Assume d = 0; OPD relative to neighbouring transparent rings = (m+½)λ/2
- Exchange opaque rings with transparent material, thickness t
  - t = λ/2δ ⇒ extra phase shift of π
  - t ~ 4.9 μm for 2-Å radiation and diamond
  - Max. efficiency = $3/\pi^2$ (for t = λ/2δ, δ ≫ β)



$$P_{n+1} - P_n = (m + 1/2)\lambda$$

$$\phi = \frac{2\pi\delta t}{\lambda}$$



See also: Section 5.5.3 of Intro to Synchrotron Radiation, PRW, or http://zoneplate.lbl.gov/theory

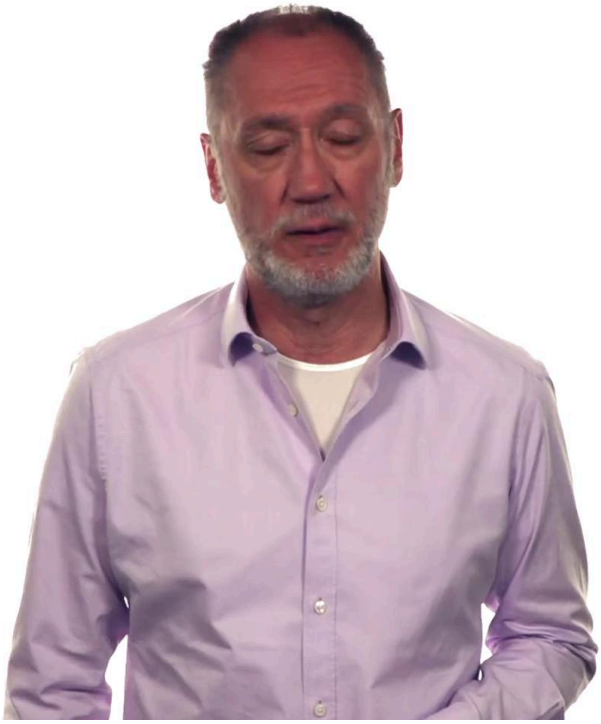
Phase zone plates are an interesting variant of Fresnel zone plates, in which the opaque rings are replaced by transparent material of a certain thickness. Logically, it makes sense that if one ignores the ring thickness, the phase difference between the P M plus one ring and the PN ring is Pi radians. In other words, any radiation passing through the PN plus one ring will be destructive relative to the radiation passing through the PN ring. But if we now make the ring thickness T of a transparent material such that the radiation passing through this material advances by Lamda upon two, compared to radiation passing through its neighbour, then the total effect is to make the contributions from every ring constructively interfering. The thickness T that satisfies this is when T is equal to Lambda divided by two Delta. In the case of diamond at two angstroms, this equates to a thickness of nearly five microns. The theoretical maximum efficiency of a phase zone plate is three divided by Pi squared, or around 30 percent, assuming negligible absorption, and T equals Lambda divided by two Delta.

Notes

Summary

5m 15s

In the next video...



In the final video of this section, we will explore the use of capillary lenses, and also the recent addition to the palette of available microfocusing X-ray elements, namely multilayer Laue lenses.

Notes

Summary

6m 42s