Scalar Diffraction

From experimental observations it is known that longer wavelengths are diffracted at larger angles, and that tighter focal spots are obtained from larger-aperture lenses. This has led to the formulation of the fundamental relation for a diffraction angle θ_d being proportional to the wavelength of light λ, and inversely proportional to the size D of the propagating wave:

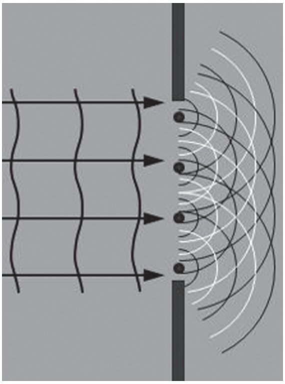
$$\theta_d \propto \lambda/D$$

Solutions to a diffraction problem consider the spatial evolution of finite-sized waves and waves whose propagation was disrupted by amplitude or phase objects. Rigorous solutions to diffraction problems satisfy **Maxwell's equations** and the appropriate boundary conditions. A simpler approach is based on the **Huygens-Fresnel principle**, which defines the foundation for scalar diffraction theory.

Scalar diffraction theory assumes that the propagating field can be treated as a scalar field. The propagation of a field described by its **complex amplitude** $U(x,y,z)$ in free space from the object plane ($z = 0$) to the observation plane is governed by the **Helmholtz equation**:

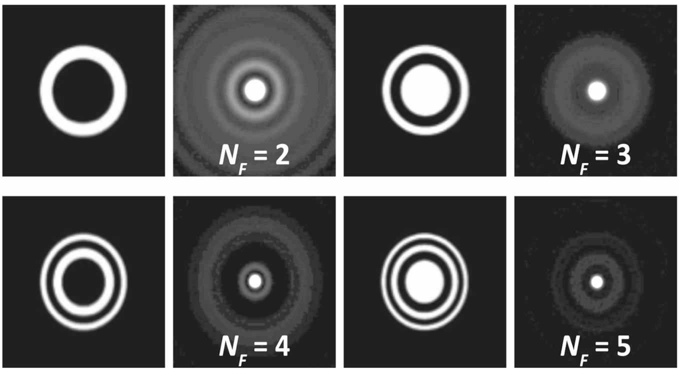
$$\nabla^2 U(x,y,z) + k_0^2 U(x,y,z) = 0$$

in which $k_0 = |k_0| = 2\pi/\lambda_0$ is the free space **wave number**. According to Huygens' principle, the propagating field at the aperture is considered as a superposition of several secondary point sources with spherical wavefronts. Fresnel stated that intensity distribution after the aperture is the result of interferometric interaction between the Huygens point sources.

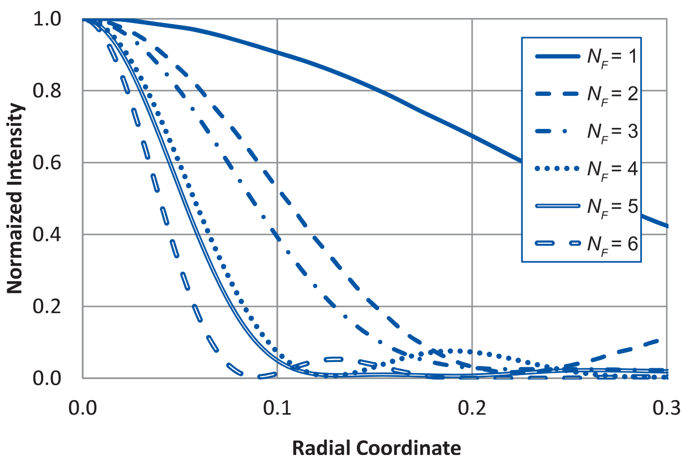


Fresnel Zone Plates

A **Fresnel zone plate (FZP)** represents an amplitude mask that consists of alternating opaque and transparent rings. Each ring size corresponds to a Fresnel zone as defined by the observation point. FZPs are often employed in lieu of lenses to concentrate the propagating field into a tight on-axis spot.

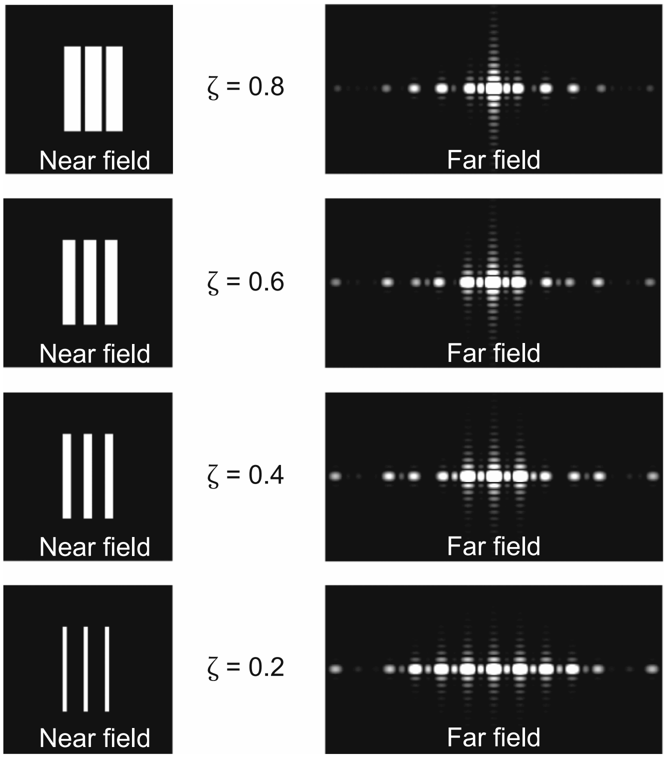


Increasing the number of zones progressively reduces the width, as well as increases the peak intensity and the total power contained in the central peak of the diffraction pattern.



Aperture Fill Factor

The near-field aperture **duty cycle**, also known as a **fill factor** ζ, is defined as the ratio of the aperture width w to the aperture spacing value d ($\zeta = w/d$). The effects of the duty cycle changes on the shape of a diffraction pattern are shown for three rectangular apertures:



An increase in the duty cycle leads to a reduction in the number of high-peak-intensity nodes, as well as an increase in the energy concentration in the central diffraction spot.

In the limiting case of $\zeta = 1$, the pattern becomes identical to an entirely filled single rectangular aperture with a width of $3w$ and a height h.

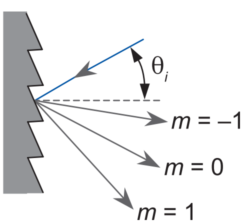
Diffraction Gratings

Diffraction gratings are periodic diffractive structures that modify the amplitude or phase of a propagating field. **Linear gratings** represent the simplest periodic diffractive structures.

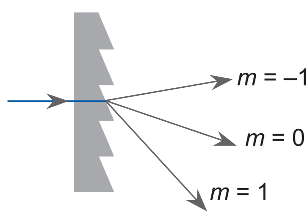
Amplitude gratings are based on the amplitude modulation of the incident wavefront and are employed in spectral regions where nonabsorbing optical materials are not available. The amplitude modulation is associated with transmission losses introduced by the grating.

Phase gratings are based on the phase modulation of the incident wavefront by introducing a periodic phase delay to the individual portions of the propagating wavefront. Phase gratings are designed to work in **transmission**, **reflection**, or in a bidirectional manner.

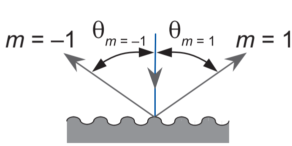
Surface-relief phase gratings are based on wavefront-division interference principles and introduce periodic phase delays to the fractions of the incident wavefront due to periodic changes of the substrate thickness.



Reflective surface-relief phase grating with triangular profile



Transmissive surface-relief phase grating with triangular profile



Reflective surface-relief phase grating with sinusoidal profile