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Light distributions in front of a circular aperture, evaluated using vector diffraction theory

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Abstract: For a plane wave (having wavelength λ) incident on a circular aperture (radius a), the transverse distribution of light intensity beyond the aperture is expressed in terms of a dimensionless parameter, $p_1=a/\lambda$, for various distances close to the aperture, using the vector Rayleigh-Sommerfeld diffraction theory.

Two dimensional intensity distribution of light in front of apertures, having sizes of the same order or smaller than the wavelength of light, are usually calculated using the FDTD (Finite Difference Time Domain) method. Rayleigh-Sommerfeld wave propagation theory also provides the integral expressions for the electric fields for arbitrary distances in front of the aperture. However, the evaluation of the diffraction integrals has historically been very time consuming for small distances in front of the aperture. With the increased computational power available on desktop computers, it is now possible to evaluate the full two-dimensional distribution of light in front of apertures for distances 'very' close to the aperture in reasonable times of evaluation (within minutes). In this work, the electric field in front of the aperture is expressed in terms of dimensionless integrals, with normalized distances $x_1 = x/a$, $y_1 = y/a$ and $z_1 = z/z_0$, where $z_0 = (2\pi a^2)/\lambda$. and $p_1 = (2\pi a)/\lambda$. For incident light linearly polarized in the x direction with amplitude E_0, the vector components E_x and E_z beyond the aperture are given by:

$$E_x(x_1,y_1,z_1) = -iE_0\frac{p_1^2}{2\pi}z_1A_1(x_1,y_1,z_1) \text{ , and } E_z(x_1,y_1,z_1) = iE_0\frac{p_1}{2\pi}A_2(x_1,y_1,z_1) \quad (1)$$

where

$$A_1(x_1,y_1,z_1) = \int_{-1}^{1}\int_{-\sqrt{1-y_{01}^2}}^{\sqrt{1-y_{01}^2}} f(\rho_1)dx_{01}dy_{01}\text{, and } A_2(x_1,y_1,z_1) = \int_{-1}^{1}\int_{-\sqrt{1-y_{01}^2}}^{\sqrt{1-y_{01}^2}}(x_1-x_{01})f(\rho_1)dx_{01}dy_{01}\,. \quad (2)$$

The functions f and ρ_1 are defined as

$$f(\rho_1) = \frac{e^{ip_1\rho_1}}{\rho_1^2}(1-\frac{1}{ip_1\rho_1})\text{, and } \rho_1(x_1,y_1,z_1,x_{01},y_{01}) = \sqrt{(x_1-x_{01})^2+(y_1-y_{01})^2+p_1^2z_1^2} \quad (3)$$

For $p_1 = 2\pi$, the Rayleigh-Sommerfeld expression can be evaluated accurately for distances as close the aperture as $z_1 = 10^{-8}$. The Poynting vectors are also evaluated denoting the intensity distribution of light at various planes in front of the aperture. It is shown that for $p_1 = 2\pi$, the vector theory needs to be considered up to longitudinal distances from the aperture $z_1 \sim 0.1$.

[1] R.K. Luneburg, in *Mathematical Theory of Optics*, (University of California Press, Berkeley, CA, 1964).