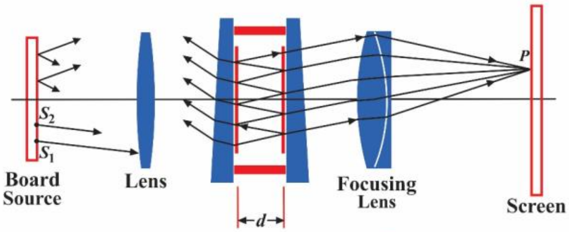

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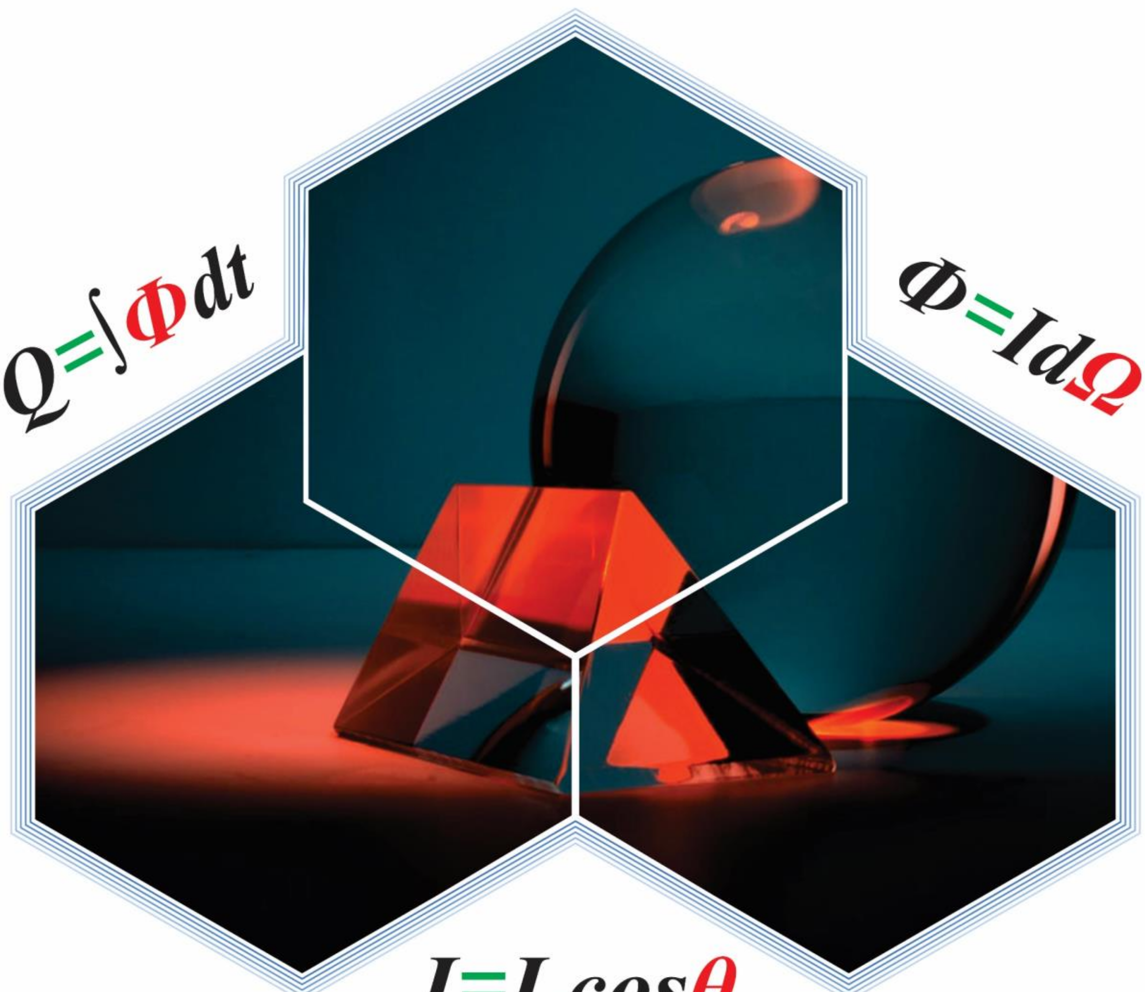

$Q = \int \Phi\, dt$

$\Phi = I\, d\Omega$

$I = I_0 \cos\theta$

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Hammad Abbas
Dr. Syed Hamad Bukhari

TEACH YOURSELF

OPTICS

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For **BS/M.Sc Physics** students of all Pakistani Universities/Colleges

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Contents

Chapter 1

Introduction to Optics

NO SOLVED PROBLEMS ARE THERE FOR CHAPTER 1

Chapter 2

Wave Motion

SOLVED PROBLEMS

Problem: 2.1- A Nd:YAG laser puts out a beam of 1.06 μm electromagnetic radiation in vacuum. Determine

(a) the beam's temporal frequency.

(b) its temporal period

(c) its spatial frequency.

Solution

(a)- Since $v = \nu\lambda$

$$\nu = -\frac{v}{\lambda} = \frac{2.99 \times 10^{8}\, m/s}{1.06 \times 10^{-6}\, m} = 2.82 \times 10^{14}\, Hz = 282\, THz$$

(b)- The temporal period is

$$\tau = \frac{1}{\nu} = \frac{1}{2.82} \times 10^{14}\, Hz = 3.55 \times 10^{-15}\, s = 3.55\, fs$$

(c)- The spatial frequency is

$$k = \frac{1}{\lambda} = \frac{1}{1.06} \times 10^{-6}\, m = 943 \times 10^{3}\, m^{-1}$$

That is, 943 thousands waves per meter

Problem: 2.2- A propagating wave at time $t = 0$ can be expressed in SI units as $\psi(y, 0) = (0.030\,m)\cos(\pi y/2.0)$. The disturbance moves in the negative y-direction with a phase velocity of $2.0\,m/s$. Write an expression for the wave at a time of $6.0\,s$

Solution

Write the wave in the form

$$\psi(y,t) = A\cos 2\pi\left(\frac{y}{\lambda} \pm \frac{t}{\tau}\right)$$

Here $A = 0.030\,m$ and

$$\psi(y,0) = (0.030\,m)\cos 2\pi\left(\frac{y}{4.0}\right)$$

We need the period and since $\lambda = 4.0\,m$, $v = \nu\lambda = \lambda/\tau$; $\tau = \lambda/v = (4.0\,m)/(2.0\,m/s) = 2.0\,s$. Hence

$$\psi(y,t) = (0.030\,m)\cos 2\pi\left(\frac{y}{4.0} + \frac{t}{2.0}\right)$$

The positive sign in the phase indicates motion in the negative y-direction. At $t = 6.0\,s$

$$\psi(y,6.0) = (0.030\,m)\cos 2\pi\left(\frac{y}{4.0} + 3.0\right)$$

Problem: 2.3- An electromagnetic plane wave is described by its electric field E. The wave has an amplitude E_0, an angular frequency ω, a wavelength λ, and travels at speed c outward in the direction of the unit propagation vector

$$\hat{k} = \frac{(4\hat{i} + 2\hat{j})}{\sqrt{20}}$$

(not to be confused with the unit basis vector $\hat{k}$). Write an expression for the scalar value of the electric field E.

Solution

We want and equation of the form $E(x, y, z, t) = E_0 e^{i\hat{k}\cdot(\vec{r}-\omega t)}$. Here

$$\vec{k}\cdot\vec{r} = \frac{2\pi}{\lambda}\hat{k}\cdot\vec{r} = \frac{2\pi}{\lambda\sqrt{20}}(4\hat{i} + 2\hat{j})\cdot(x\hat{i} + y\hat{j} + z\hat{k}) = \frac{\pi}{\lambda\sqrt{5}}(4x + 2y)$$

Hence

$$E = E_0 e^{i\left[\frac{\pi}{\lambda\sqrt{5}}(4x+2y)-\omega t\right]}$$

Problem: 2.4- A convex lens of focal length $10\,cm$ is used as a magnifying glass. Find the magnifying power,

(a)- The image is formed at infinity.

(b)- The image is formed at least distance of distinct vision (25 cm from the lens).

Solution

(a)- When image is formed at infinity

$$M = \frac{D}{f} = \frac{25}{10} = 2.5$$

(a)- When image is formed at the least distance of distinct vision (25 cm from the lens).

$$M = 1 + \frac{D}{f} = 1 + \frac{25}{10} = 3.5$$

Problem: 2.5- Show explicitly that when $\vec{E}_y(z,t)$ lags $\vec{E}_x(z,t)$ by 2π the resulting wave is given by,

$$\vec{E} = (\hat{i}E_{0_x} + \hat{j}E_{0_y})\cos(kz - \omega t)$$

Solution

When $\vec{E}_y(z,t)$ lags by 2π

$$\vec{E} = \hat{i}E_{0_x}\cos(kz-\omega t) + \hat{j}E_{0_y}\cos(kz-\omega t+2\pi)$$

Using the identity

$$\cos(x \pm y) = \cos x \cos y \mp \sin x \sin y$$

The resultant wave becomes

$$\vec{E} = \hat{i}E_{0_x}\cos(kz-\omega t) + \hat{j}E_{0_y}[\cos(kz-\omega t)\cos 2\pi - \sin(kz-\omega t)\sin 2\pi]$$

And also

$$\vec{E} = (\hat{i}E_{0_x} + \hat{j}E_{0_y})\cos(kz-\omega t)$$

Which was to be proven.

Chapter 3

Maxwell Equations in Free Space

SOLVED PROBLEMS

Problem: 3.1- Imagine a harmonic plane electromagnetic wave traveling in the z-direction in a homogeneous isotropic dielectric. If the wave, whose amplitude is E_0, has a magnitude of zero at $t = 0$ and $z = 0$,

(a) Show that its energy density is given by

$$u(t) = \epsilon E_0^2 \sin^2 k(z - vt)$$

(b) Find an expression for the irradiance of the wave.

Solution

(a)- From equation $u = u_E + u_B$ applied to a dielectric,

$$u = \frac{\epsilon}{2}E^2 + \frac{1}{2\mu}B^2$$

Where

$$E = E_0 \sin k(z - vt)$$

Using $E = vB$

$$u = \frac{\epsilon}{2}E^2 + \frac{1}{2\mu}\frac{E^2}{v^2} = \epsilon E^2 = \epsilon E_0^2 \sin^2 k(z - vt)$$

(b)- The irradiance follows from equation,

$$S = \frac{uc\Delta tA}{\Delta tA} = uc$$

namely, $S = uv$, and so

$$S = \epsilon v E_0^2 \sin^2 k(z - vt)$$

Whereupon

$$I = \langle S \rangle_T = \frac{1}{2}\epsilon v E_0^2$$

Problem: 3.2- The electric field of an electromagnetic plane wave is expressed as

$$\vec{E} = (-2.99\,V/m)\hat{j}e^{i(kz-\omega t)}$$

Given that $\omega = 2.99 \times 10^{15}\,rad/s$ and $k = 1.00 \times 10^7\,rad/m$, find

(a) The associated vector magnetic field.

(b) The irradiance of the wave.

Solution

(a)- The wave travels in the $+z$-direction. $\vec{E_0}$ is in the $-\hat{j}$ or $-y$-direction. Since $\vec{E} \times \vec{B}$ is in the $\hat{k}$ or $+z$-direction, $\vec{B_0}$ must be in the $\hat{i}$ or $+x$-direction. $E_0 = vB_0$ and $v = \omega/k = 2.99 \times 10^{15}/1.00 \times 10^7 = 2.99 \times 10^8\,m/s$ and so

$$\vec{B} = \left(\frac{2.99\,V/m}{2.99 \times 10^8\,m/s}\right)\hat{i}e^{i(kz-\omega t)} \;=\; (10^{-8}\,T)\hat{i}e^{i(kz-\omega t)}$$

(b)- Since the speed is $2.99 \times 10^8\,m/s$ we are dealing with vacuum, hence

$$I = \frac{c\epsilon_0}{2}E_0^2 \;=\; \frac{(2.99 \times 10^8\,m/s)(8.854 \times 10^{-12}\,C^2/N \cdot m^2)}{2}(2.99\,V/m)^2 \;=\; 0.0118\,W/m^2$$

Problem: 3.3- An electromagnetic wave travels through a homogeneous dielectric medium with a frequency of $\omega = 2.10 \times 10^{15}\, rad/s$ and $k = 1.10 \times 10^{7}\, rad/m$. The $\vec{E}$-field of the wave is

$$\vec{E} = (180\, V/m)\hat{j}e^{i(kx-\omega t)}$$

Determine,

(a) The direction of $\vec{B}$.

(b) The speed of the wave.

(c) The associated $\vec{B}$-field.

(d) The index of refraction.

(e) The permittivity.

(f) The irradiance of the wave.

Solution

(a)- $\vec{B}$ is in the direction of $\hat{k}$, since the wave moves in the direction of $\vec{E} \times \vec{B}$ and that is in the $\hat{i}$ or $+x$-direction.

(b)- The speed is $v = \omega/k$

$$v = \frac{2.10 \times 10^{15}\, rad/s}{1.10 \times 10^{7}\, rad/m} = 1.909 \times 10^{8}\, m/s \quad \text{or} \quad 1.91 \times 10^{8}\, m/s$$

(c)- $E_0 = vB_0 = (1.909 \times 10^{8}\, m/s)B_0$

$$B_0 = \frac{180\, V/m}{1.909 \times 10^{8}\, m/s} = 9.43 \times 10^{-7}\, T = (9.43 \times 10^{-7}\, T)\hat{k}e^{i(kx-\omega t)}$$

(d)- $n = c/v$

$$n = (2.99 \times 10^{8}\, m/s)/(1.909 \times 10^{8}\, m/s) = 1.5663, \quad \text{Or} \quad 1.57$$

(e)- $n = \sqrt{K_E}$

$$\Rightarrow \quad n^2 = K_E \quad \text{and} \quad K_E = 2.453$$
$$\epsilon = \epsilon_0 K_E = (8.8542 \times 10^{-12})2.453 = 2.172 \times 10^{-11}\, C^2/N \cdot m^2$$

(f)- $I = \frac{\epsilon v}{2}E_0^2$

$$I = \frac{(2.172 \times 10^{-11}\, C^2/N \cdot m^2)(1.909 \times 10^8\, m/s)(180\, V/m)^2}{2} = 67.2\, W/m^2$$

Chapter 4

Polarization

SOLVED PROBLEMS

Problem: 4.1- If the plane of vibration of the incident beam makes an angle of 30° with the optic axis, compare the intensities of extraordinary and ordinary light

Solution

Intensity of the extraordinary ray

$$I_E = A^2 \cos^2 \theta$$

Intensity of the ordinary ray,

$$I_{()} = A^2 \sin^2 \theta$$

$$\frac{I_E}{I_{()}} = \frac{A^2 \cos^2 \theta}{A^2 \sin^2 \theta} = \frac{\cos^2 \theta}{\sin^2 \theta}$$

Here, $\theta = 30°$

$$\therefore \qquad E = \frac{I_E}{I_{()}} = 3$$

Problem: 4.2- Calculate the thickness of a double refracting plate capable of producing a path difference of $\frac{\lambda}{4}$ between extraordinary and ordinary waves

Solution

$$\lambda = 5890\,\text{Å}, \qquad \mu_\circ = 1.53 \quad \text{and} \quad \mu_E = 1.54$$

Here, $$(\mu_E - \mu_\circ)t = \frac{\lambda}{4}$$

$$t = \frac{\lambda}{4(\mu_E - \mu_\circ)}$$

Here, $$\lambda = 5890\,\mathring{A} = 5.89 \times 10^{-7}\,m$$

$$t = \frac{5.89 \times 10^{-7}}{4(1.54 - 1.53)} = 1.47 \times 10^{-5}\,m = 1.47 \times 10^{-2}\,mm$$

Chapter 5

Wavefront Splitting Interferometer

SOLVED PROBLEMS

Problem: 5.1- Two parallel narrow horizontal slits in an opaque vertical screen are separated center-to-center by $2.644\,mm$. These are directly illuminated by yellow plane waves from a filtered discharge lamp. Horizontal fringes are formed on a vertical viewing screen $4.500\,m$ from the aperture plane. The center of the fifth bright band is $5.000\,mm$ above the center of the zeroth or central bright band.

(a) Determine the wavelength of the light in air.

(b) If the entire space is filled with clear soybean oil ($n = 1.4729$), where would the fifth fringe now appear?

Solution

(a)- The problem states that $Y_5 = 5.000\,mm$ and from equation, $y_m \approx \frac{S}{a}m\lambda$ We know that in air

$$y_m \approx \frac{S}{a}m\lambda_0$$

Where $S = 4.500\,m$, $a = 2.644\,mm$ and λ_0 is to be found.

Hence

$$\lambda_0 = \frac{ay_5}{s5} = \frac{(2.644 \times 10^{-3}\, m)(5.000 \times 10^{-3}\, m)}{(4.500\, m)5}$$

$$\Rightarrow \qquad \lambda_0 = 587.56\, nm$$

Or to four significant figures

$$\lambda_0 = 587.6\, nm$$

(b)- When the space is filled with oil the wavelength will decrease, whereupon the new fringe location (y'_m) will be closer to the center of the apparatus. Thus

$$y'_m = \frac{S}{a} m \left(\frac{\lambda_0}{n}\right) = \frac{y_m}{n}$$

$$\Rightarrow \qquad y'_m = \frac{5.000 \times 10^{-3}\, m}{1.4729}$$

$$\text{Finally,} \qquad y'_5 = 3.395\, mm$$

Problem: 5.2- Considering the double mirror,

(a) Show that the fringe separation is given by,

$$\varDelta_y \approx \frac{(R+d)\lambda}{a}$$

Where λ is the wavelength of the illumination in the surrounding medium.

(b) Prove that,

$$\varDelta_y \approx \frac{(R+d)\lambda}{2R\theta}$$

Solution

(a)- From Young's experiment

$$\varDelta_y \approx \frac{S}{a}\lambda$$

And the same is true here, where $S = \overline{DP} \approx R + d$. Accordingly,

$$\varDelta_y \approx \frac{(R+d)\lambda}{a}$$

(b)- To get θ involved notice that in triangle S_1CD

$$\frac{a}{2} = R \sin\theta \approx R\theta$$

And so $$\Delta_y \approx \frac{(R+d)\lambda}{2R\theta}$$

Problem: 5.3- The yellow D_1 line from a sodium discharge lamp has a vacuum wavelength of 5895.923 Å. Suppose such light falls at 30.00° on the surface of a film of soybean oil ($n = 1.4729$) suspended (within a wire frame) in air. What minimum thickness should the film have in some region if that area is to strongly reflect the light?

Solution

The equation $d\cos\theta_t = (2m+1)\frac{\lambda_f}{4}$ pertains to reflected maxima:

$$d\cos\theta_t = (2m+1)\frac{\lambda_f}{4}$$

Here we want the minimum thickness, which corresponds to the minimum value of m, namely, zero. Hence

$$d\cos\theta_t = \frac{\lambda_f}{4}$$

It is needed to be computed both λ_f and θ_t. Using Snell's law

$$n_i \sin\theta_i = n_t \sin\theta_t$$

It follows that

$$\sin\theta_t = \frac{\sin 30.00°}{1.4729} = 0.3395$$

And $\theta_t = 19.844°$. Consequently,

$$d = \frac{\lambda_f}{4}\frac{1}{\cos 19.844°}$$

At this point we need to use that fact $\lambda_f = \frac{\lambda_0}{n_f}$, whereupon

$$d = \frac{\lambda_0}{4n_f}\frac{1}{\cos 19.844°}$$

Hence

$$d = \frac{589.59 \times 10^{-9}}{4(1.4729)} \frac{1}{0.94062}$$

And

$$d = 1.064 \times 10^{-7}\, m$$

The minimum thickness is a mere

$$d = 106.4\, nm$$

Problem: 5.4- A wedge-shaped air film is illuminated by yellow sodium light ($\lambda_0 = 589.3\, nm$, the center of the doublet). The center of the 173$^{\text{rd}}$ maximum will be how far from the apex if the wedge angle is 0.50°?

Solution

We could use either

$$x_m = \frac{(m + \frac{1}{2})\lambda_f}{2\alpha}$$

Where $m = 0, 1, 2, \cdots$ or

$$x_{m'} = \frac{(m' - \frac{1}{2})\lambda_f}{2\alpha}$$

Where $m' = 1, 2, 3, \cdots$. In both cases we will need α in radians:

$$\alpha = \left(\frac{\pi\ rad}{180°}\right) 0.50° = 8.727 \times 10^{-3}\, rad$$

Consequently,

$$x_m = x_{172} = \frac{(172 + \frac{1}{2})589.3 \times 10^{-9}}{2(8.727 \times 10^{-3})} = 5.8\, mm$$

Or

$$x_{m'} = x_{173} = \frac{(173 + \frac{1}{2})589.3 \times 10^{-9}}{2(8.727 \times 10^{-3})} = 5.8\, mm$$

Problem: 5.5- Green light of wavelength 5100 Åfrom a narrow slit is incident on a double slit. If the overall separation of 10 fringes on a screen 200 cm away is 2 cm, Find the slit separation.

Solution

$$\beta = \frac{\lambda D}{d}$$

Hence

$$\lambda = 5100 \times 10^{-8}\, cm \qquad d = 7$$
$$D = 200\, cm$$
$$10\,\beta = 0.2\, cm$$

Or

$$d = \frac{\lambda D}{\beta}$$
$$d = \frac{5100 \times 10^{-8} \times 200}{0.2}$$
$$d = 0.051\, cm$$

Problem: 5.6- Two coherent sources are 0.18 mm apart and the fringes are observed on a screen 80 cm away. It is found that with a certain monochromatic source of light, the fourth bright fringe is situated at a distance of 10.8 mm from the central fringe. Calculate the wavelength of light.

Solution

Here, $D = 80\, cm$, $d = 0.18\, mm = 0.018\, cm$
$n = 4$, $x = 10.8\, mm = 1.08\, cm$,
$\lambda = ?$

$$x = \frac{n\lambda D}{d}$$
$$\lambda = \frac{xd}{nD} = \frac{1.08 \times 0.018}{4 \times 80}$$
$$= 6075 \times 10^{-8}\, cm = 6075\,\text{Å}$$

Problem: 5.7- Two straight and narrow parallel slits $1\,mm$ apart are illuminated by monochromatic light. Fringes formed on the screen held at a distance of $100\,cm$ from the slits are $0.50\,mm$ apart. What is the wavelength of light?

Solution

$$\beta = 0.50\,mm = 0.05\,cm$$

$$d = 1\,mm = 0.1\,cm$$

$$D = 100\,cm$$

$$\beta = \frac{\lambda D}{d}$$

$$\lambda = \frac{\beta d}{D} = \frac{0.05 \times 0.1}{100} = 5 \times 10^{-5}\,cm = 5000\,\text{Å}$$

Chapter 6

Introduction To Diffraction

SOLVED PROBLEMS

Problem: 6.1- In Fraunhofer diffraction due to a narrow slit a screen is placed $2\,m$ away from the lens to obtain the pattern. If the slit width is $0.2\,mm$ and the first minima lie $5\,mm$ on either side of the central maximum, find the wavelength of light.

Solution

In the case of Fraunhofer diffraction at a narrow rectangular aperture,

$$a\sin\theta = n\lambda$$

$$n = 1$$

$$\therefore \quad a\sin\theta = \lambda$$

$$\sin\theta = \frac{x}{D}$$

$$\therefore \quad \frac{ax}{D} = \lambda$$

$$\lambda = \frac{ax}{D}$$

Here,

$$a = 0.2\,mm = 0.02\,cm$$

$$x = 5\,mm = 0.5\,cm$$

$$D = 2\,m = 200\,cm$$

$$\therefore \qquad = \frac{0.02 \times 0.5}{200}$$
$$\lambda = 5 \times 10^{-5}\, cm$$
$$\lambda = 5000\, \mathring{A}$$

Problem: 6.2- A single slit of width $0.14\, mm$ is illuminated normally by a monochromatic light and diffraction bands are observed on a screen $2\, m$ away. If the center of the second dark band is $1.6\, cm$ from the middle of the central bright band, deduce the wavelength of light used.

Solution

In the case of Fraunhofer diffraction at a narrow rectangular slit,

$$a \sin\theta = n\lambda$$

Here θ gives the direction of the minimum

$$n = 2$$
$$\lambda = ?$$
$$a = 0.14\, mm = 0.14 \times 10^{-3}\, m$$
$$D = 2\, m$$
$$x = 1.6\, cm = 1.6 \times 10^{-2}\, m$$
$$\sin\theta = \frac{x}{D} = \frac{n\lambda}{a}$$
$$\therefore \qquad \lambda = \frac{xa}{nD}$$
$$= \frac{1.6 \times 10^{-2} \times 0.14 \times 10^{-3}}{2 \times 2}$$
$$= 5.6 \times 10^{-7}\, m = 5600\, \mathring{A}$$

Problem: 6.3- Diffraction pattern of a single slit of width $0.5\,cm$ is formed by a lens of focal length $40\,cm$. Calculate the distance between the first dark and the next bright fringe from the axis. Wavelength = $4890\,\mathring{A}$.

Solution

For minimum intensity

$$
\begin{aligned}
a\sin\theta_n &= n\lambda \\
\sin\theta_n &= \frac{x_1}{f}, \qquad\qquad n = 1 \\
\frac{x_1}{f} &= \frac{\lambda}{a} \\
\text{Here} \qquad\qquad \lambda &= 4890\,\mathring{A} = 4890\times10^{-10}\,m \\
a &= 0.5\,cm = 5\times10^{-3}\,m \\
f &= 40\,cm = 0.4\,m \\
x_1 &= \frac{f\lambda}{a} \\
x_1 &= \frac{0.4\times4890\times10^{-10}}{5\times10^{-3}} \\
x_1 &= 3.912\times10^{-5}\,m
\end{aligned}
$$

For Secondary maximum

$$
a\sin\theta_n = \frac{(2n+1)\lambda}{2}
$$

For the first secondary maximum

$$
\begin{aligned}
n &= 1 \\
\sin\theta_n &= \frac{x_2}{f} \\
\frac{x_2}{f} &= \frac{3\lambda}{2a} \\
x_2 &= \frac{3\lambda f}{2a}
\end{aligned}
$$

$$x_2 = \frac{3 \times 4890 \times 10^{-10} \times 0.4}{2 \times 5 \times 10^{-3}}$$
$$x_2 = 5.868 \times 10^{-5}\, m$$
Difference
$$x_2 - x_1 = 5.868 \times 10^{-5} - 3.912 \times 10^{-5}$$
$$= 1.956 \times 10^{-5}\, m$$
$$= 1.956 \times 10^{-2}\, mm$$

Problem: 6.4- In Fraunhofer diffraction pattern due to a single slit, the screen is at a distance of $100\, cm$ from the slit and the slit is illuminated by monochromatic light of wavelength $5893\, \mathring{A}$. The width of the slit is $0.1\, mm$. Calculate the separation between the central maximum and the first secondary minimum.

Solution

For a rectangular slit,

$$x = \frac{f\lambda}{d}$$

Here

$$f = 100\, cm,$$
$$\lambda = 5893\, \mathring{A} = 5893 \times 10^{-8}\, cm$$
$$d = 0.1\, mm = 0.01\, cm$$
$$x = ?$$
$$x = \frac{100 \times 5893 \times 10^{-8}}{0.01} = 0.5893\, cm$$

Problem: 6.5- Imagine 12 narrow, parallel, long slits each b millimeters wide, each separated from the next slit by a center-to-center distance of $5b$. The apertures are illuminated normally by plane waves and produce a Fraunhofer diffraction pattern on a distant screen. Determine the relative irradiance of the first-order principal maximum compared to the zeroth-order principal maximum.

Solution

Using the equation $I(\theta) = I_0 \left(\frac{\sin\beta}{\beta}\right)^2 \left(\frac{\sin N\alpha}{\sin\alpha}\right)^2$ The principal maxima occur when $\left(\frac{\sin N\alpha}{\sin\alpha}\right) = N$ and so here

$$I(\theta) = I(0)\left(\frac{\sin\beta}{\beta}\right)^2$$

Moreover, since $a = 5b$

$$\beta = \frac{\pi}{\lambda} b \sin\theta = \frac{\pi}{\lambda}\frac{a}{5}\sin\theta = \frac{\alpha}{5}$$

The first-order maximum occurs when $\alpha = \pi$; hence, there $\beta = \frac{\pi}{5}$. And so for $m = 1$

$$I(\theta) = I(0)\left(\frac{\sin\beta}{\beta}\right)^2 = I(0)\left(\frac{\sin\frac{\pi}{5}}{\frac{\pi}{5}}\right)^2$$

Thus

$$\frac{I(\theta)}{I(0)} = \left(\frac{\sin\frac{\pi}{5}}{\frac{\pi}{5}}\right)^2 = \left(\frac{0.5878}{0.6283}\right)^2 = (0.936)^2$$

The first-order principal maximum is 0.875 times as large as the zeroth-order maximum


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