21/12/2022

Diffraction Gratings Fundamentals

Integrated Optics

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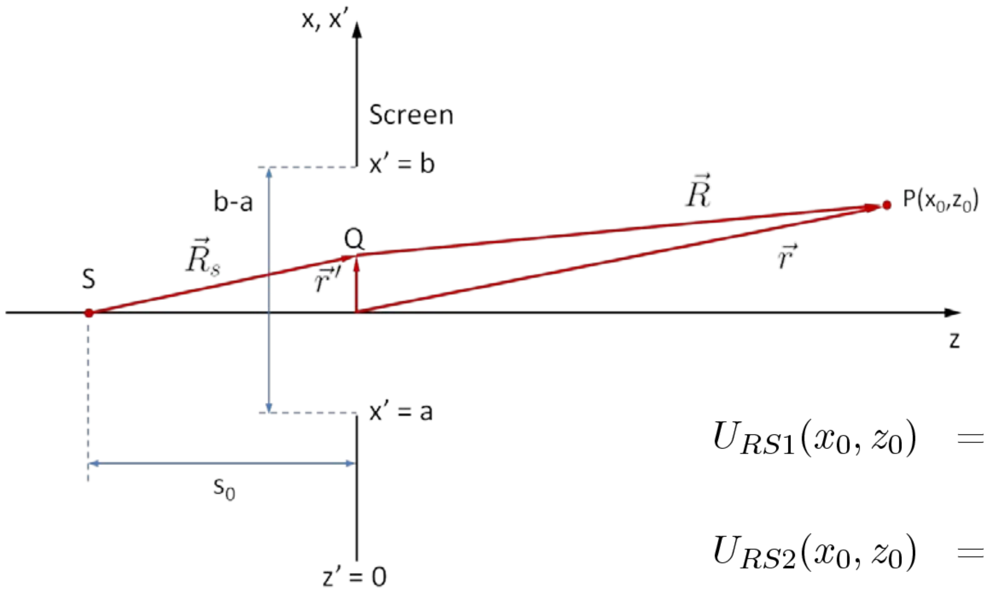
Diffraction from a Single Slit



Rayleigh-Sommerfeld Formulations

$$U_{RS1}(x_0, z_0) = \int_a^b \left[U_{inc} \frac{k}{2j} H_1^{(2)}(kR_T) \frac{z_0}{R_T} \right]_{z'=0} dx', \qquad \text{and}$$

$$U_{RS2}(x_0, z_0) = \int_a^b \left[-\frac{j}{2} H_0^{(2)}(kR_T) \frac{\partial U_{inc}}{\partial n} \right]_{z'=0} dx', \qquad \text{where,}$$

$$R_T = \left[(x_0 - x')^2 + z_0^2 \right]^{1/2}.$$

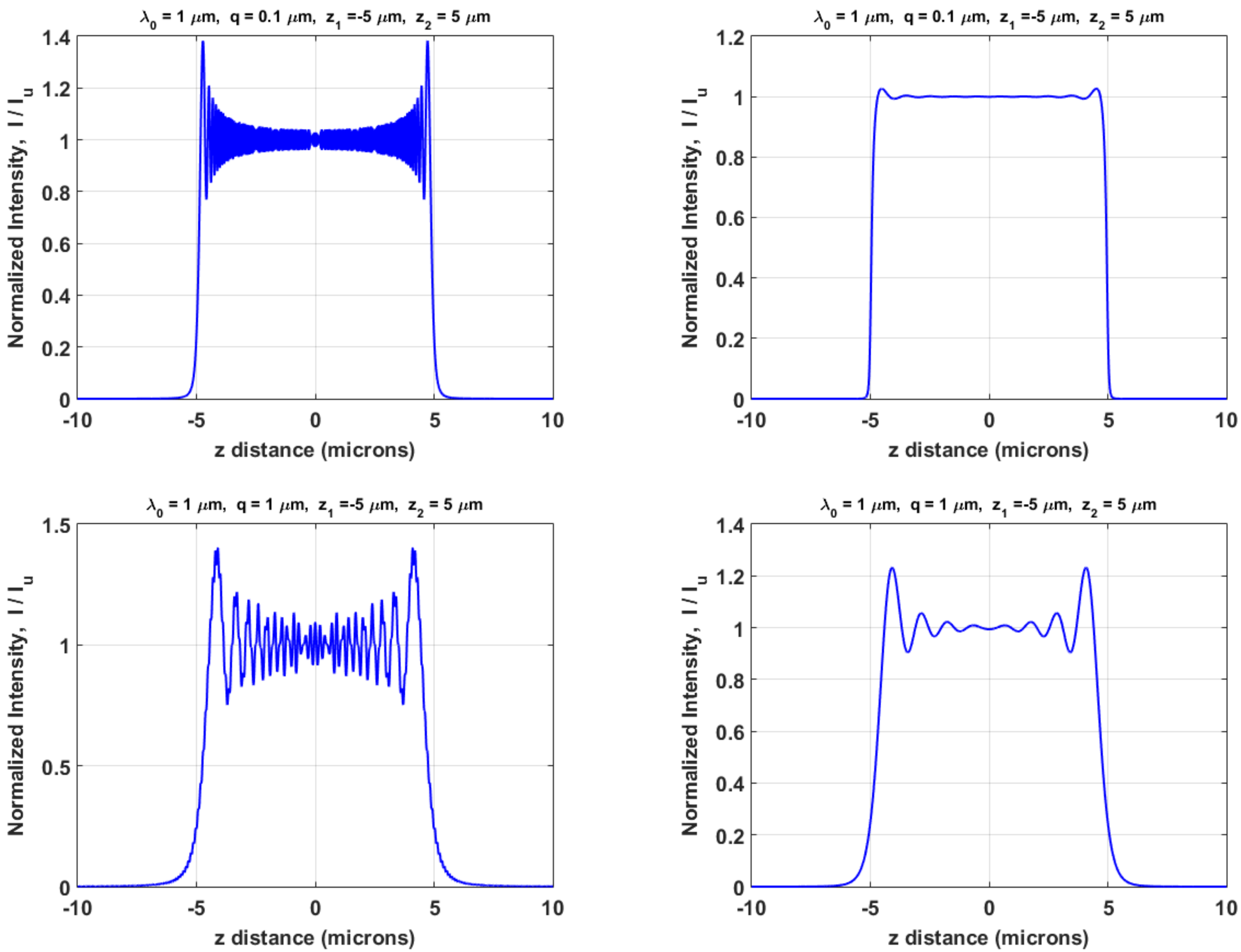
Incident Wave

$$U_{inc}(x', z') = \begin{cases} U_0 \exp(-jkz'), & \text{(plane wave)} \\ U_0 \dfrac{\exp(-jkR_s)}{\sqrt{R_s}}, & R_s = [x'^2 + (z' + s_0)^2]^{1/2}, \quad \text{(diverging)}, \\ U_0 \dfrac{\exp(+jkR_s)}{\sqrt{R_s}}, & R_s = [x'^2 + (z' - s_0)^2]^{1/2}, \quad \text{(converging)}, \end{cases}$$

Diffraction from a Single Slit

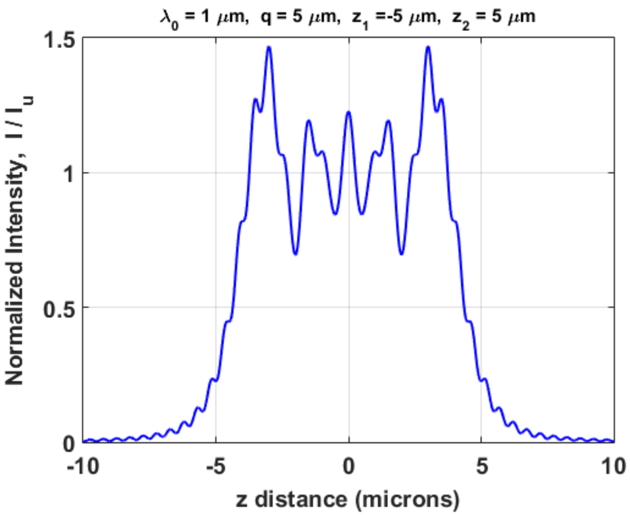
d = 10μm, λ_0 = 1μm

Rayleigh-Sommerfeld 1

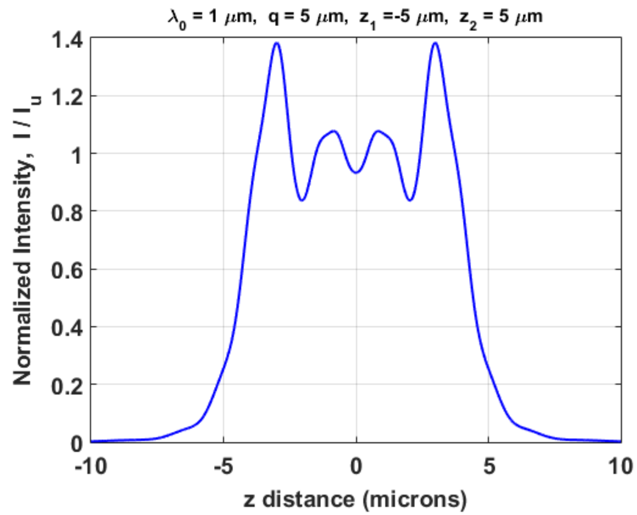


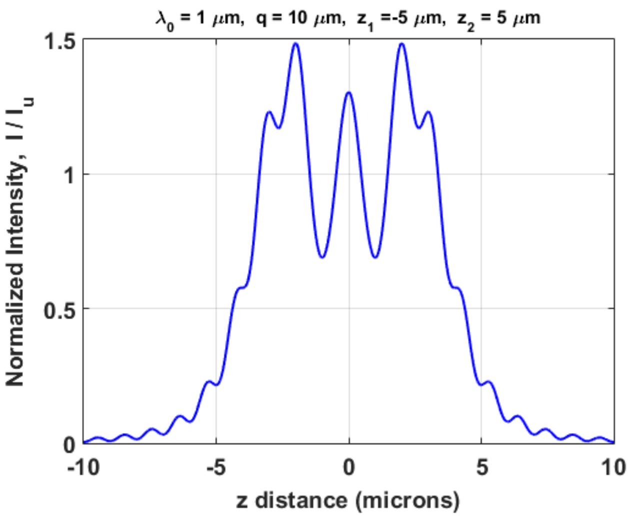
Diffraction from a Single Slit
d = 10μm, λ_0 = 1μm

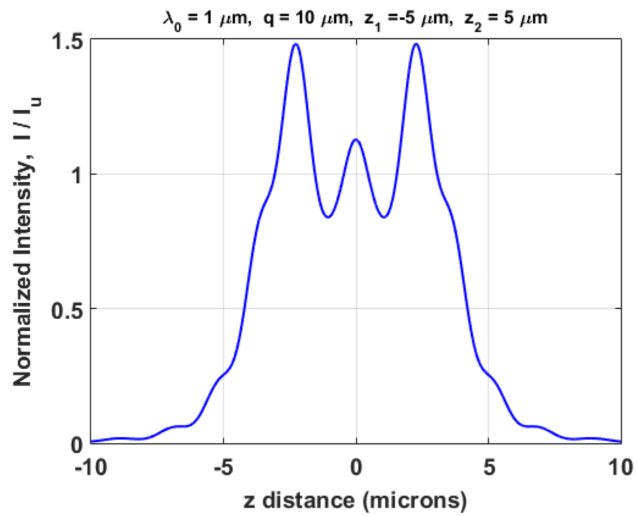
Fresnel Approximation



Rayleigh-Sommerfeld 1



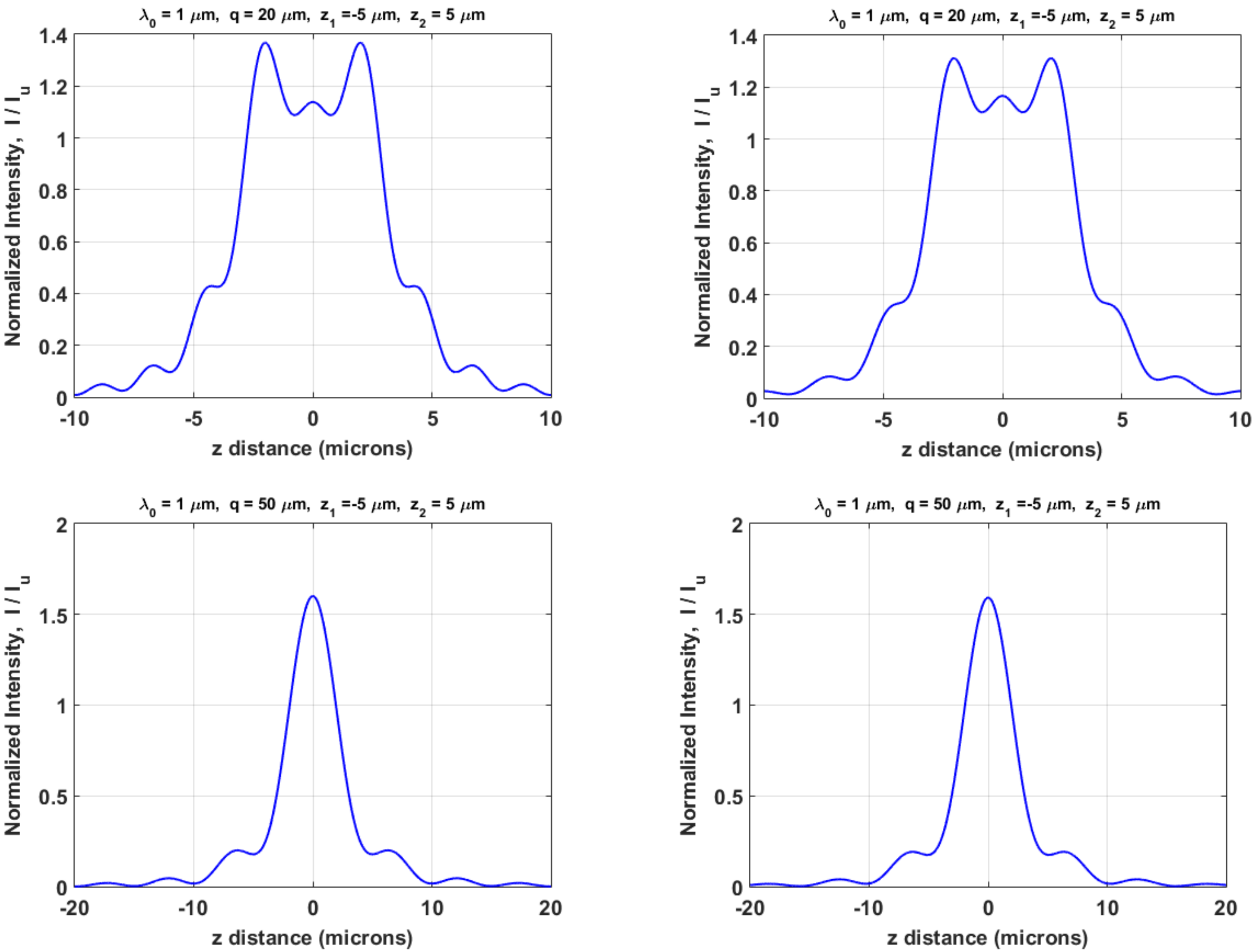




Diffraction from a Single Slit

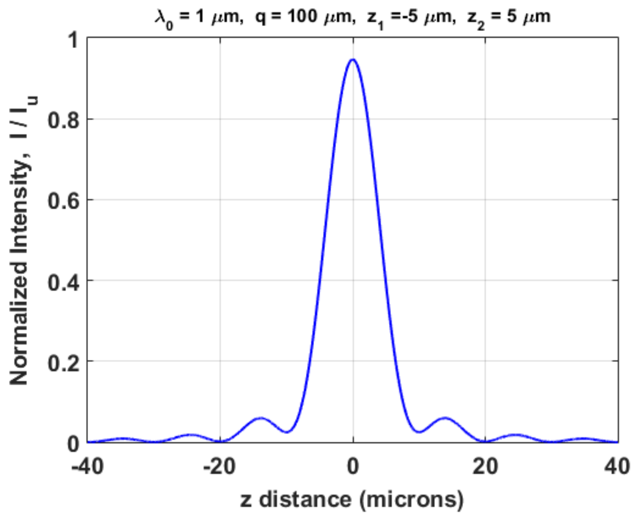
d = 10μm, λ_0 = 1μm

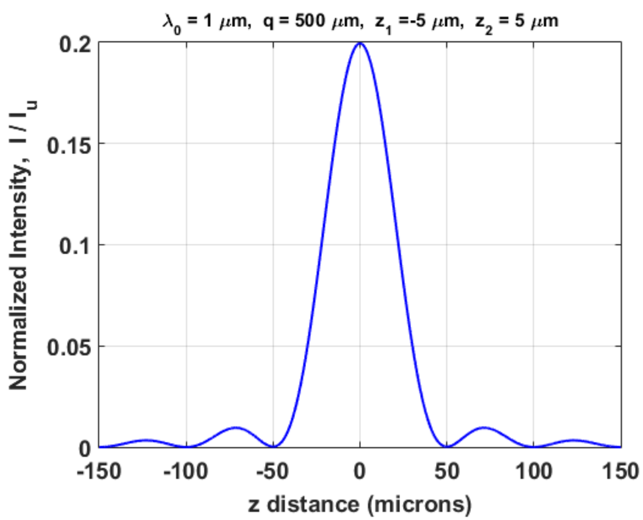
Fresnel Approximation | **Rayleigh-Sommerfeld 1**



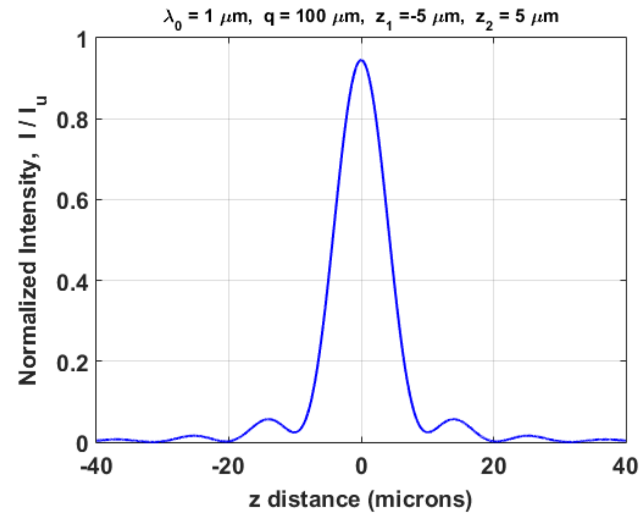
Diffraction from a Single Slit
d = 10μm, λ_0 = 1μm

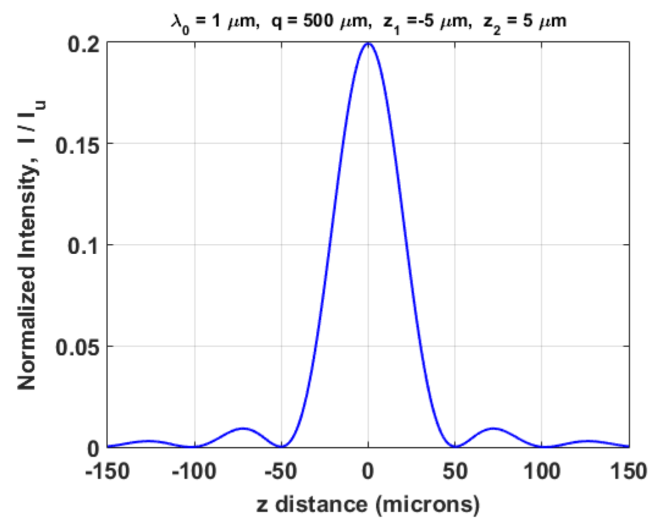
Fresnel Approximation



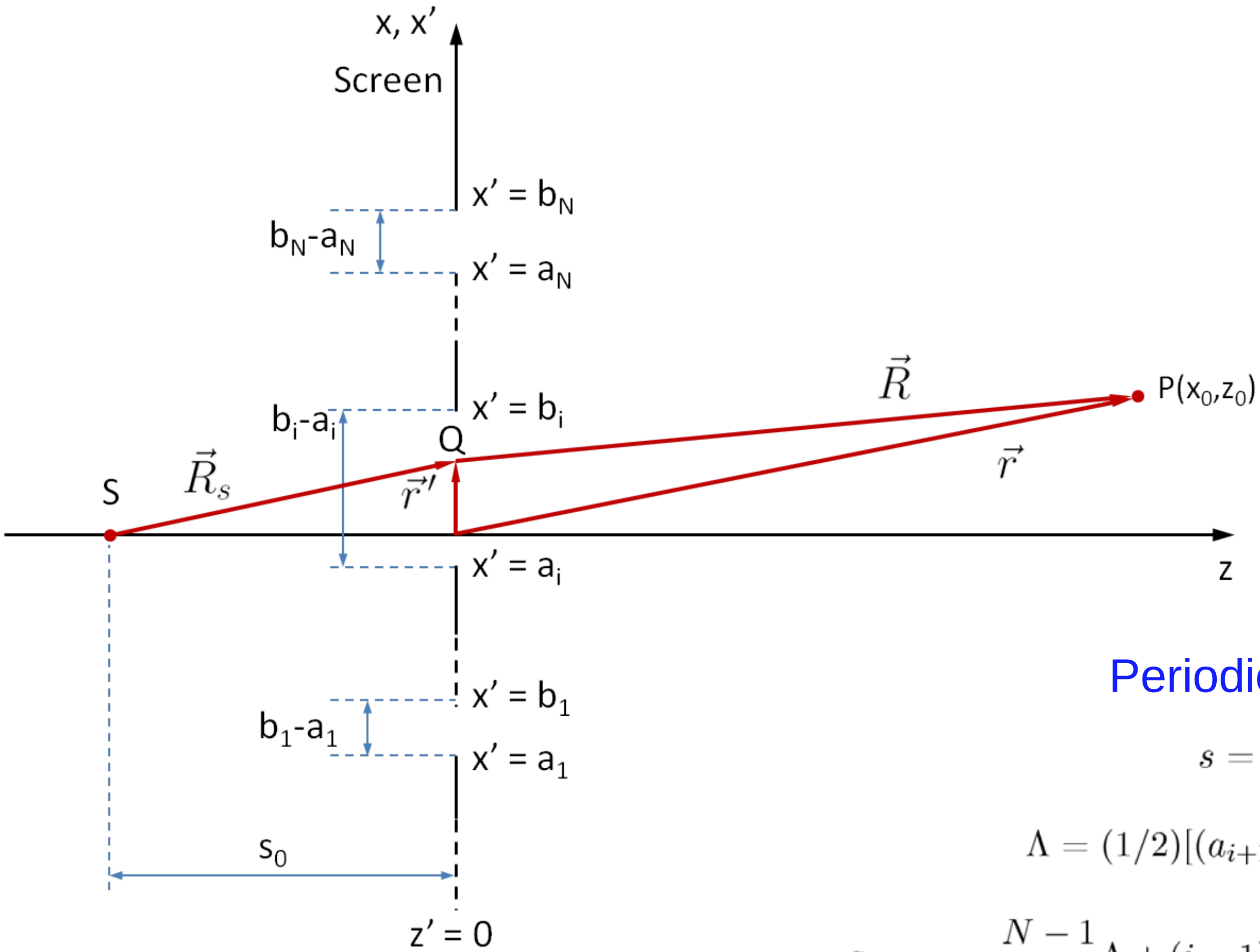


Rayleigh-Sommerfeld 1





Multiple 1D-Slit Diffraction (General Case)



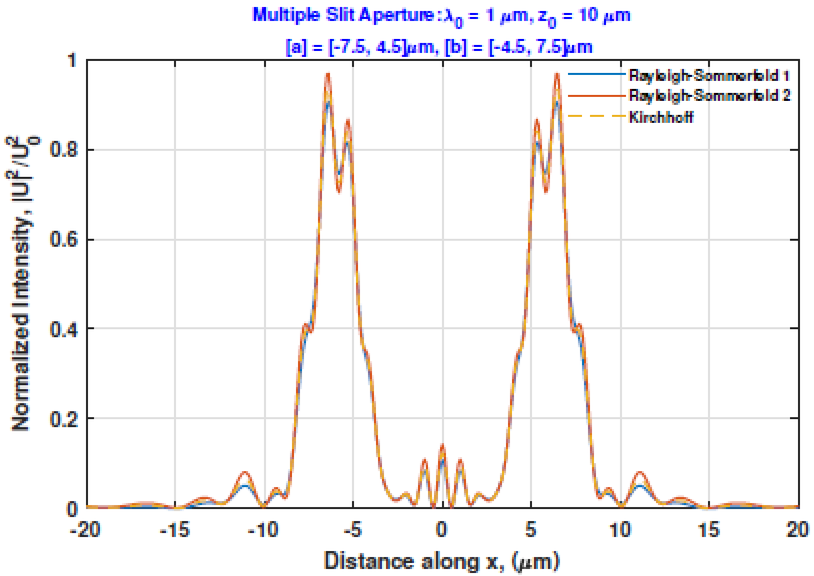
Periodic Slits

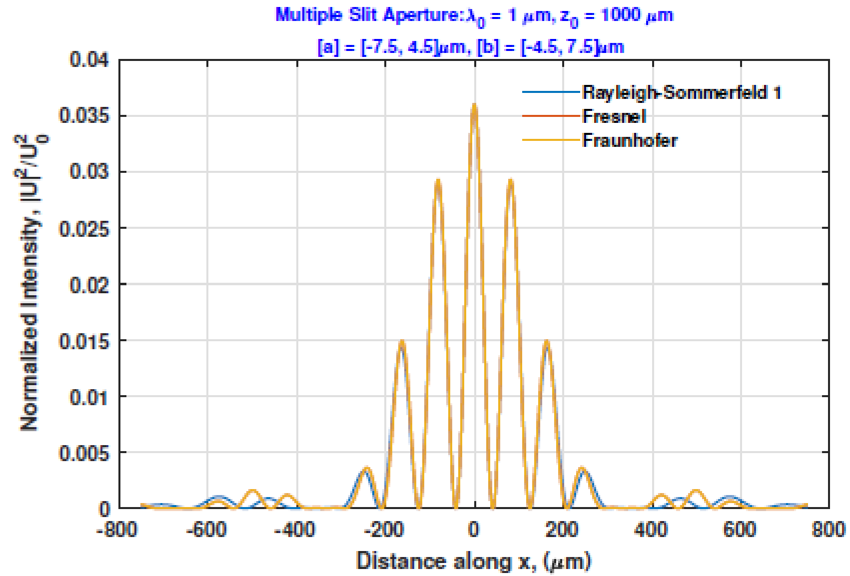
$$s = b_i - a_i$$

$$\Lambda = (1/2)[(a_{i+1} + b_{i+1}) - (a_i + b_i)]$$

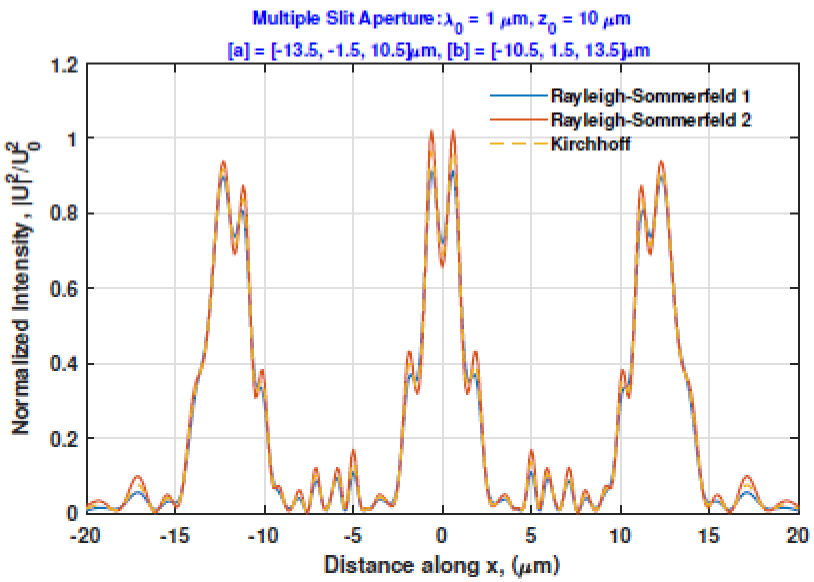
$$\begin{aligned} a_i &= -\frac{N-1}{2}\Lambda + (i-1)\Lambda - \frac{s}{2}, \\ b_i &= -\frac{N-1}{2}\Lambda + (i-1)\Lambda + \frac{s}{2}, \qquad \text{for} \quad i = 1, 2, \cdots, N \end{aligned}$$

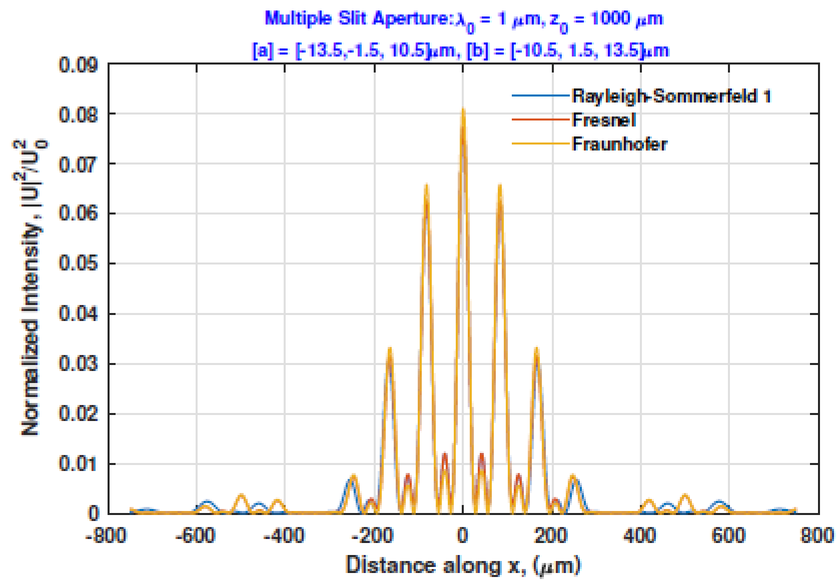
Multiple Slit Diffraction (2 slits)



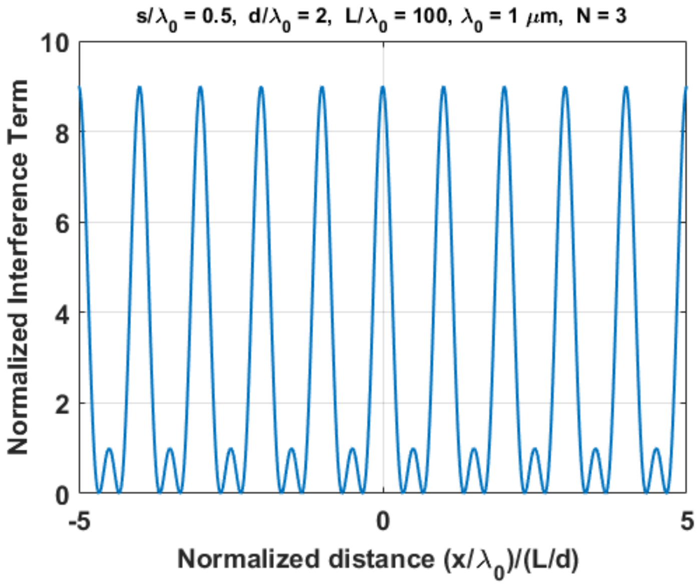


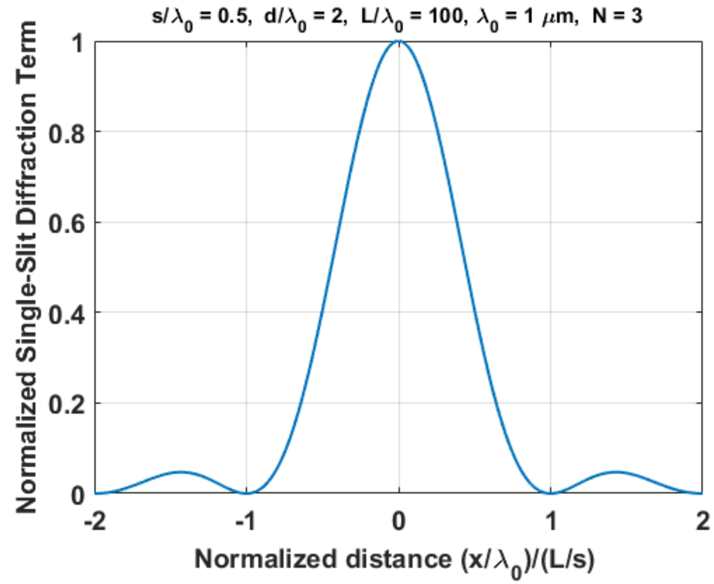
Multiple Slit Diffraction (3 slits)

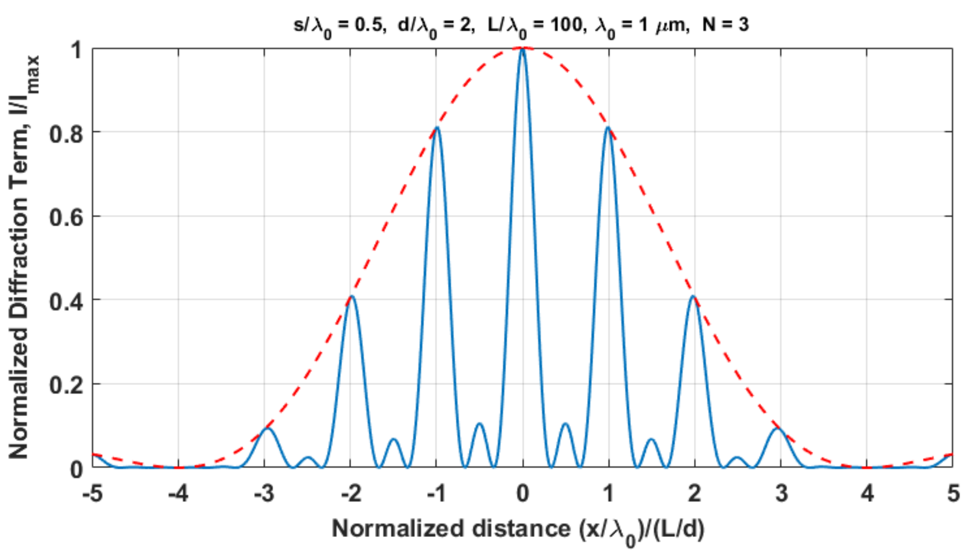




Multiple Slit Diffraction (N=3) – Fraunhofer Approximation

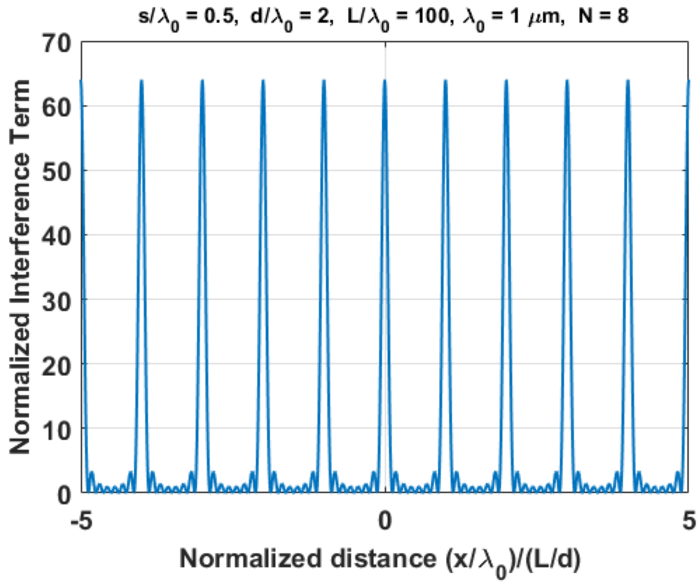


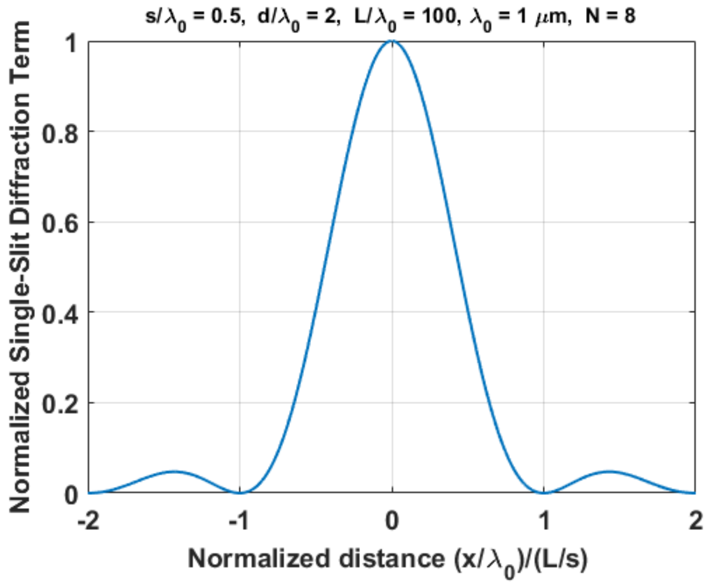


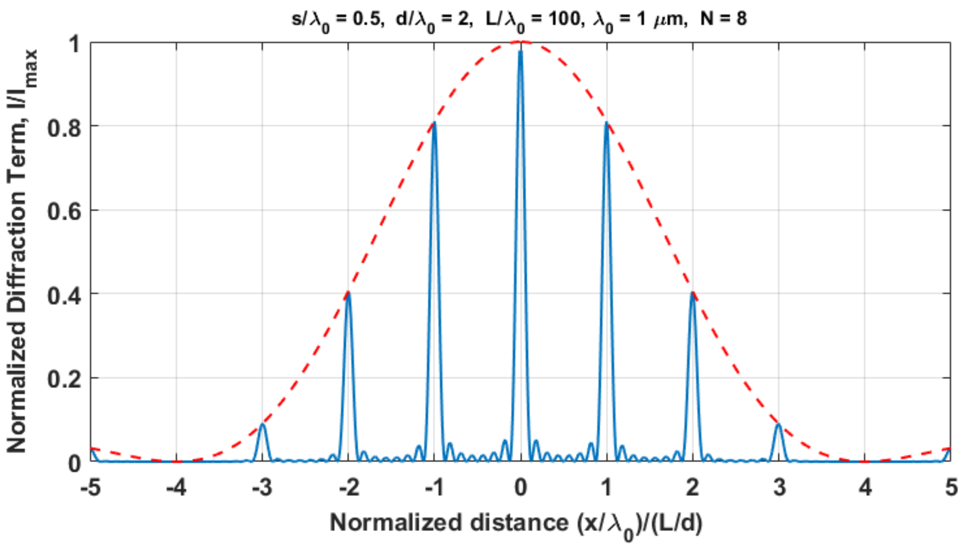


$$I_{ff} = \underbrace{\frac{|U_0|^2}{4Z}\frac{k}{2\pi z_0}s^2}_{I_0(z_0)} \underbrace{\left\{ \frac{\sin\left(\frac{kx_0}{z_0}\frac{s}{2}\right)}{\frac{kx_0}{z_0}\frac{s}{2}} \right\}^2}_{\text{slit diffraction}} \underbrace{\left\{ \frac{\sin\left(N\frac{kx_0}{z_0}\frac{\Lambda}{2}\right)}{\sin\left(\frac{kx_0}{z_0}\frac{\Lambda}{2}\right)} \right\}^2}_{\text{array factor}}$$

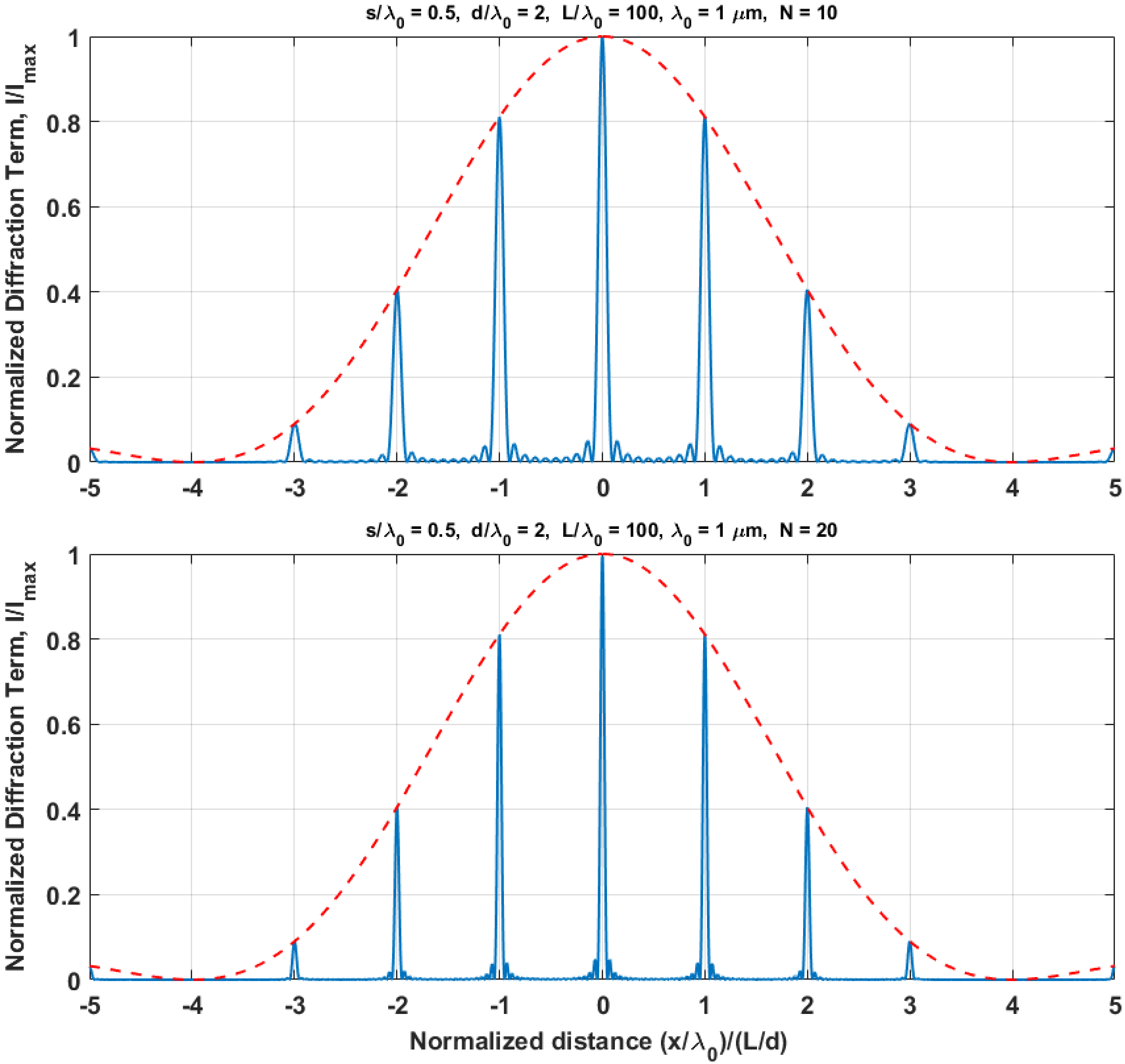
Multiple Slit Diffraction (N=8) – Fraunhofer Approximation



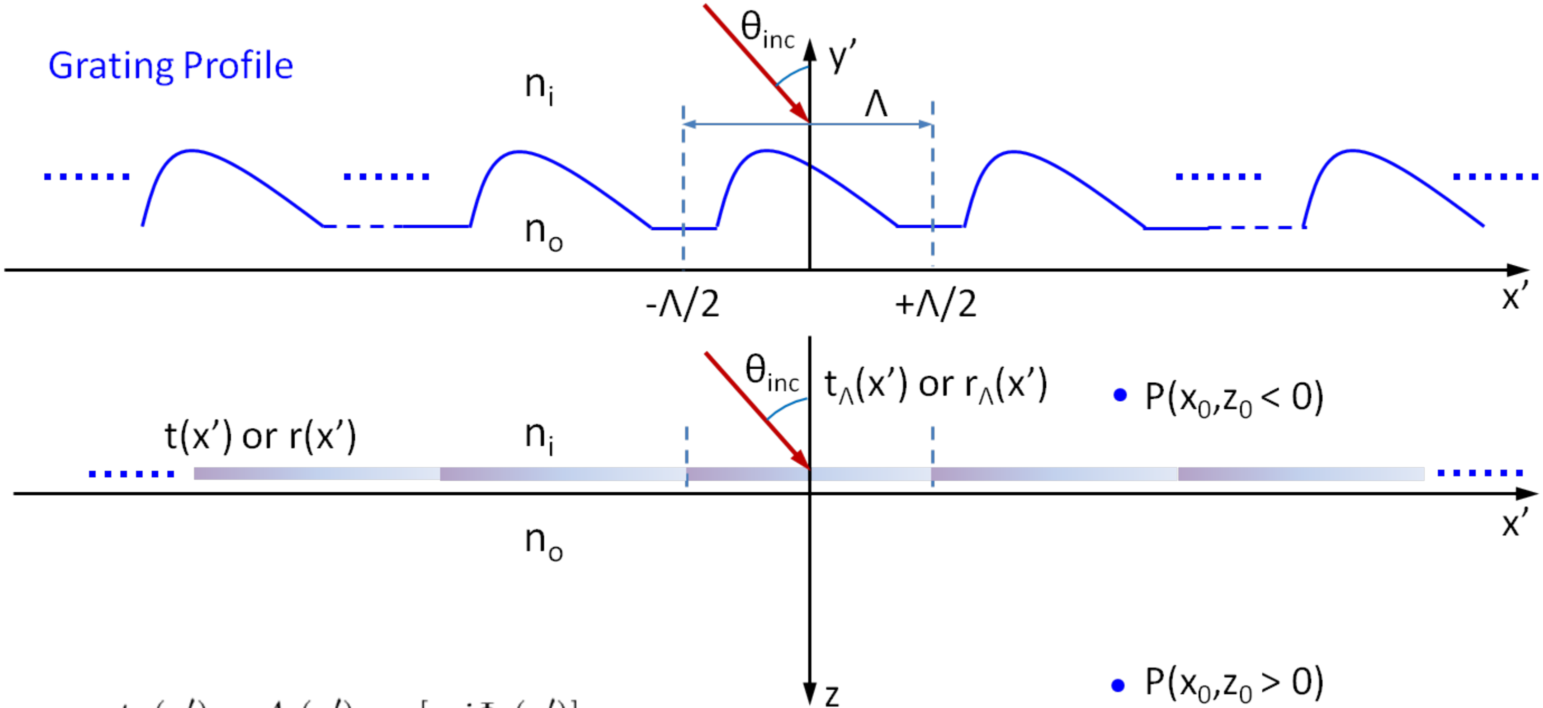




Multiple Slit Diffraction (N=10,20) – Fraunhofer Approximation



Scalar Theory of Grating Diffraction – Transmittance Approach

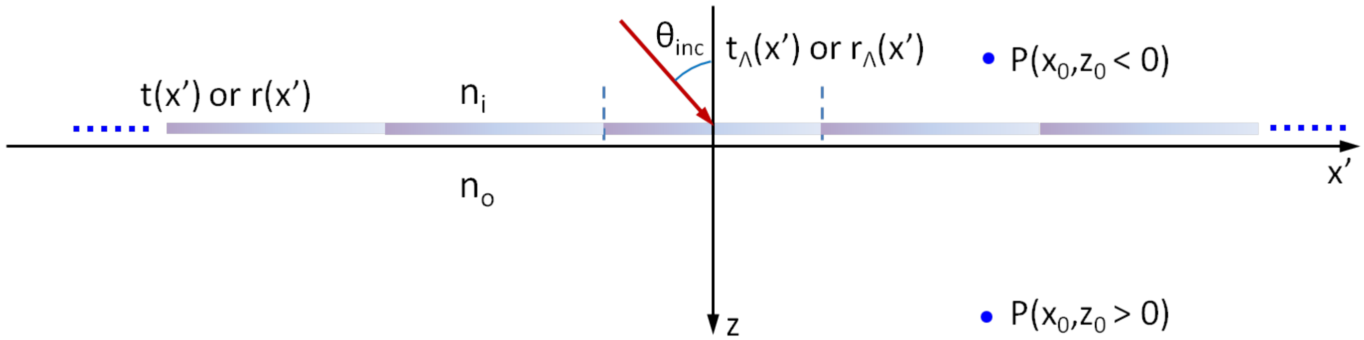


$$t_\Lambda(x') = A_t(x')\exp[-j\Phi_t(x')]$$

$$\begin{aligned} t(x') &= t(\vec{k}_{inc}) \sum_{m=-\infty}^{+\infty} t_m \exp[-jmKx'], \\ t_m &= \frac{1}{\Lambda}\mathcal{F}\{t_\Lambda(x')\}\Big|_{k_x} = \frac{1}{\Lambda}T_\Lambda(mK), \end{aligned}$$

$$U_{inc}(x', z) = U_0 \exp[-jk\sin\theta_{inc}x'] \exp[-jk\cos\theta_{inc}z].$$

Scalar Theory of Grating Diffraction – Transmittance Approach



Plane Wave Spectrum Approach

$$U(x_0, z_0) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{U}_t(k_x; z=0) e^{-j(k_x x_0 + k_z z_0)} dk_x, \qquad \text{where,}$$

$$\tilde{U}_t(k_x; z=0) = \mathcal{F}\{U_{inc}(x', z=0)t(x')\}\Big|_{k_x} = \mathcal{F}\{U_0 e^{-jk\sin\theta_{inc}x'} \sum_{m=-\infty}^{+\infty} t_m e^{-jmKx'}\}$$

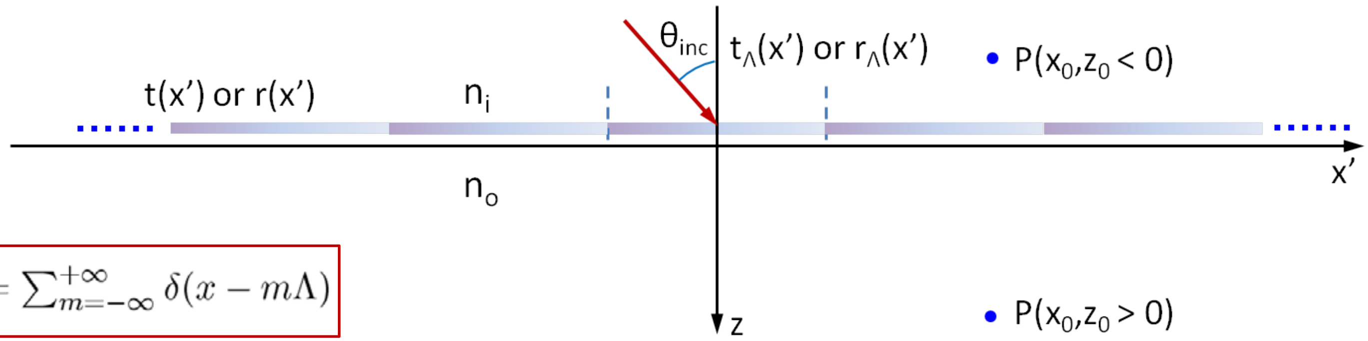
$$= U_0 \sum_{m=-\infty}^{+\infty} t_m 2\pi\delta\left(k_x - mK - k\sin\theta_{inc}\right) = 2\pi U_0 \sum_{m=-\infty}^{+\infty} t_m \delta\left(k_x - k_{xm}\right),$$

where $k_{xm} = mK + k\sin\theta_{inc}$.

$$U(x_0, z_0) = U_0 \sum_{m=-\infty}^{+\infty} t_m \exp[-jk_{xm}x_0]\exp[-jk_{zm}z_0], \qquad \text{where,}$$

$$k_{zm} = \begin{cases} \sqrt{k^2 - k_{xm}^2}, & \text{when } k \geq k_{xm}, \\ -j\sqrt{k_{xm}^2 - k^2}, & \text{when } k < k_{xm}. \end{cases}$$

Scalar Theory of Grating Diffraction – Transmittance Approach



$$\boxed{\mathrm{comb}(x;\Lambda) = \sum_{m=-\infty}^{+\infty} \delta(x - m\Lambda)}$$

Finite-Number-of-Periods

$$t(x') = \left[t_\Lambda(x') * \mathrm{comb}(x';\Lambda)\right] \mathrm{rect}\left(\frac{x'}{L}\right)$$

$$\mathcal{F}\{t(x')\}\Big|_{k_x} = \frac{1}{2\pi}\left[T_\Lambda(k_x)\frac{2\pi}{\Lambda}\sum_{m=-\infty}^{+\infty}\delta(k_x - mK)\right] * \left[L \ \mathrm{sinc}\left(\frac{k_x L}{2\pi}\right)\right] =$$

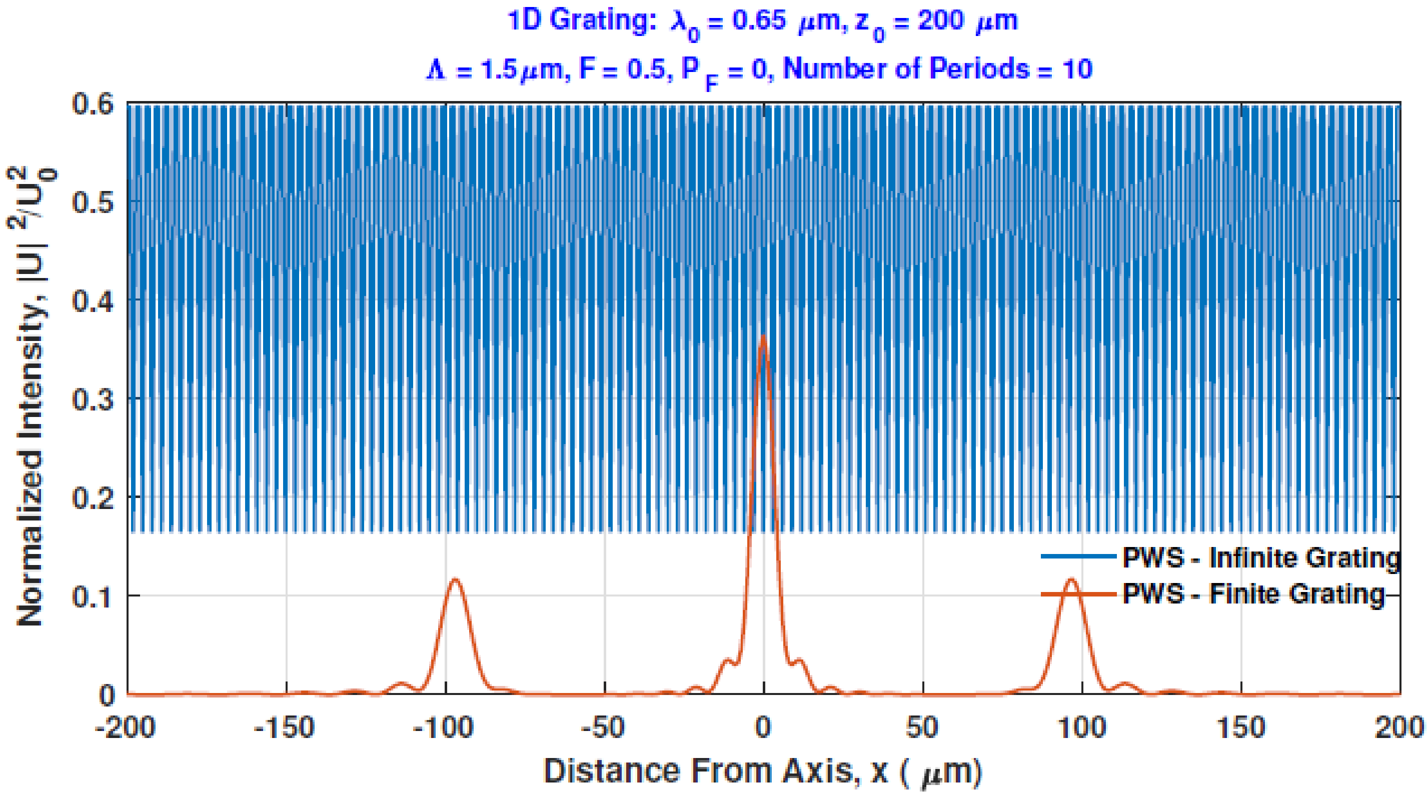
$$= L\sum_{m=-\infty}^{+\infty}\frac{1}{\Lambda}T_\Lambda(mK) \ \mathrm{sinc}\left(\frac{(k_x - mK)L}{2\pi}\right).$$

$$U(x_0,z_0) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{U}_t(k_x;z=0)e^{-j(k_x x_0 + k_z z_0)}dk_x, \qquad \text{where,}$$

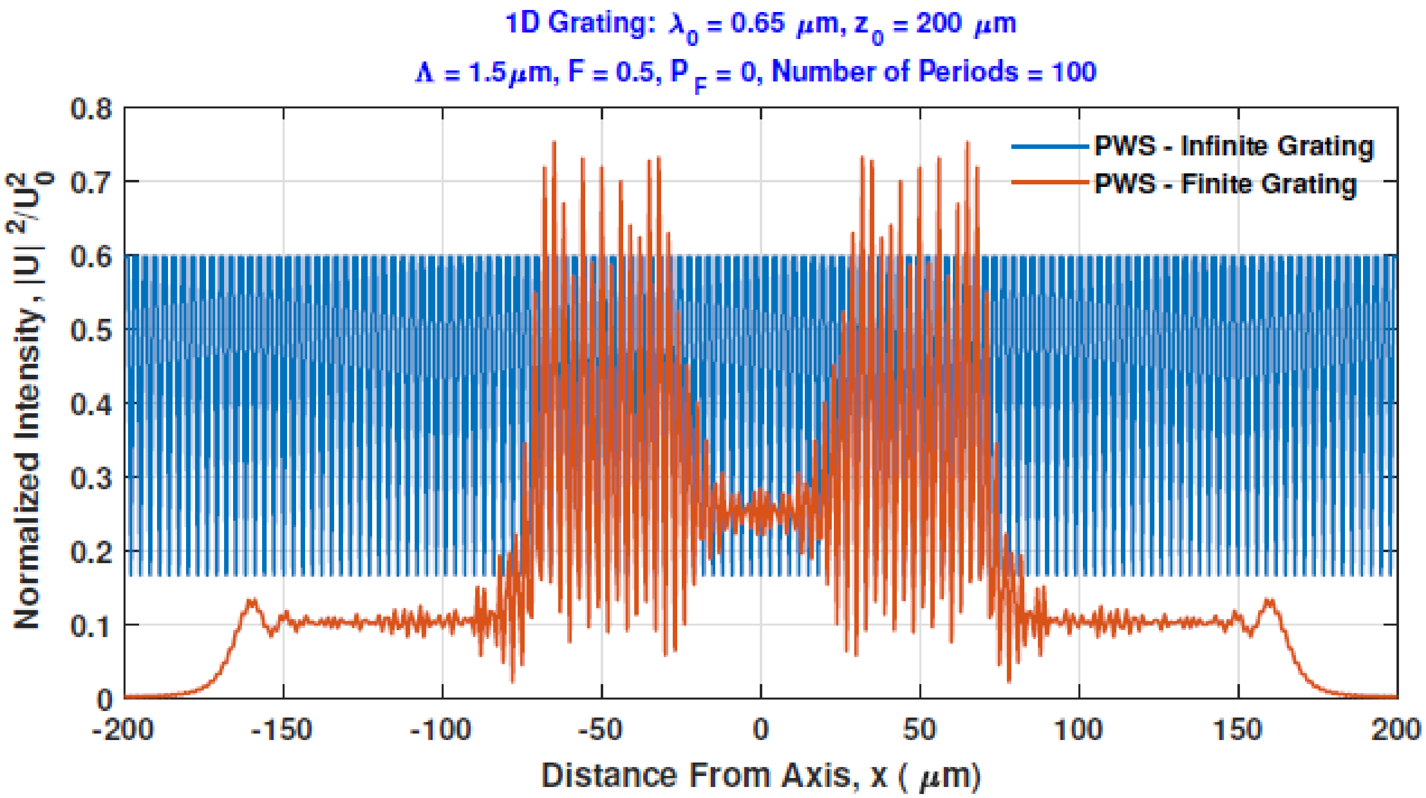
$$\tilde{U}_t(k_x;z=0) = \mathcal{F}\{U_{inc}(x',z=0)t(x')\}\Big|_{k_x} = U_0 L\sum_{m=-\infty}^{+\infty}\frac{1}{\Lambda}T_\Lambda(k_{xm}) \ \mathrm{sinc}\left(\frac{(k_x - k_{xm})L}{2\pi}\right)$$

$$= U_0 L\sum_{m=-\infty}^{+\infty} t_m \ \mathrm{sinc}\left(\frac{(k_x - k_{xm})L}{2\pi}\right), \qquad \text{where } \ k_{xm} = mK + k\sin\theta_{inc}.$$

Scalar Theory of Grating Diffraction – Transmittance Approach
Multiple-Slit Grating

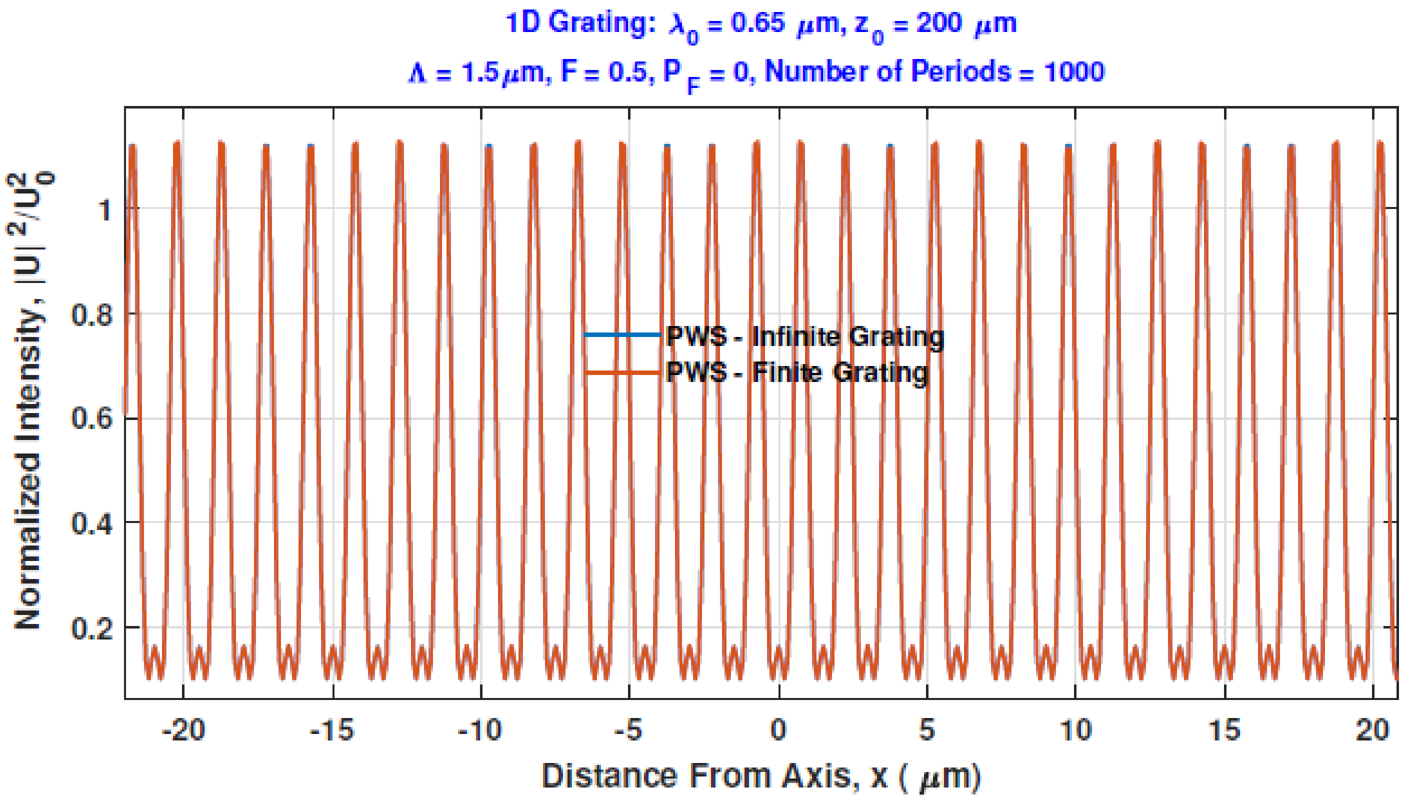


Scalar Theory of Grating Diffraction – Transmittance Approach
Multiple-Slit Grating



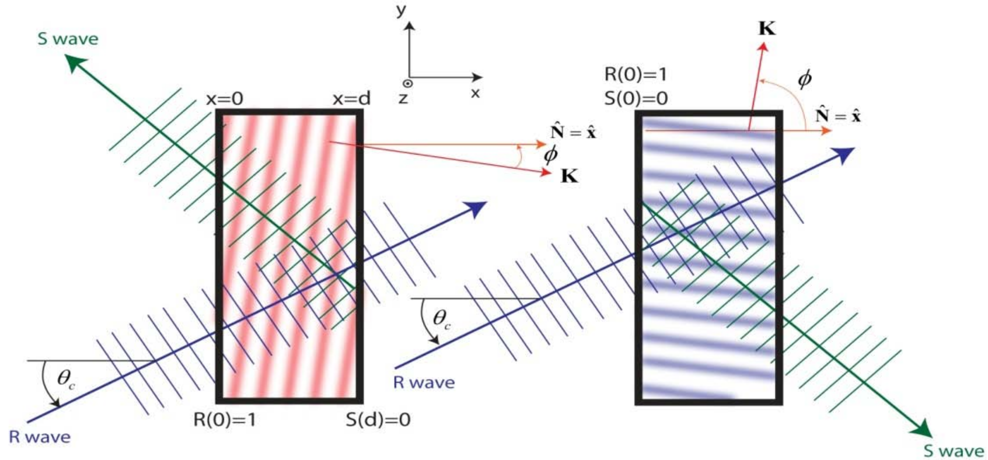
Scalar Theory of Grating Diffraction – Transmittance Approach

Multiple-Slit Grating



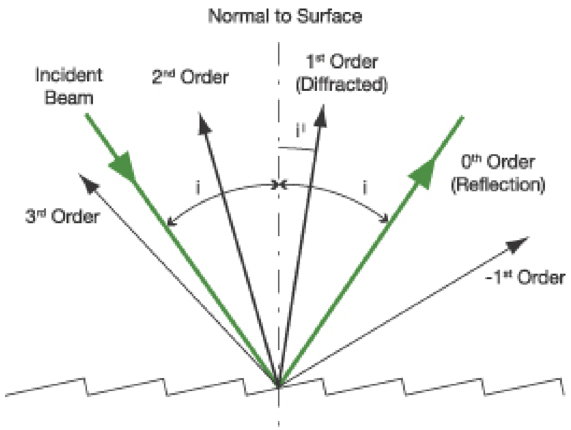
Diffraction Gratings

Example of a reflecting and transmitting holographic (volume) gratings



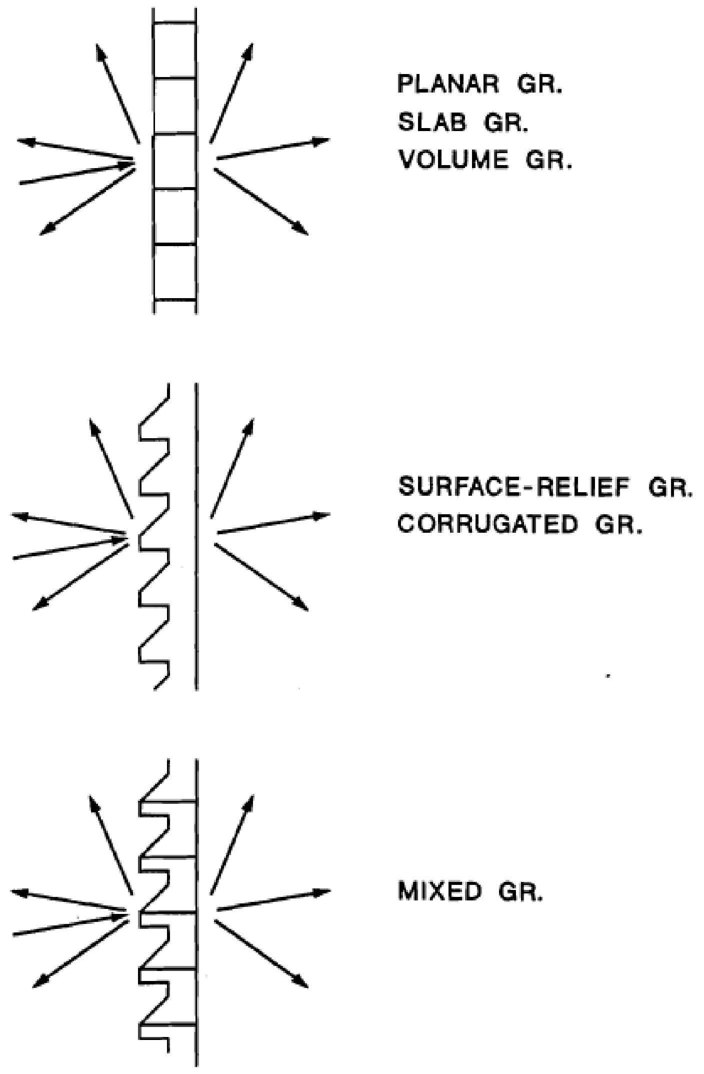
http://www.intechopen.com/books/holography-basic-principles-and-contemporary-applications/understanding-diffraction-in-volume-gratings-and-holograms

Example of a reflecting surface-relief grating

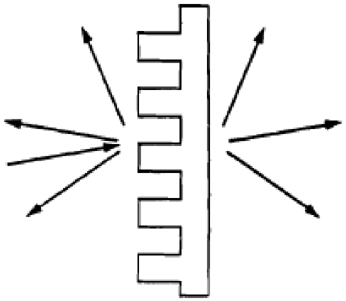


http://www.andor.com/learning-academy/diffraction-gratings-understanding-diffraction-gratings-and-the-grating-equation

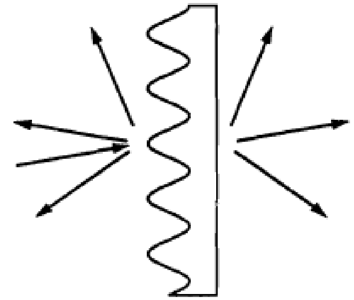
Grating Classification



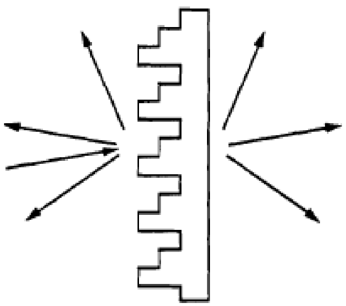
Surface-Relief Grating Types



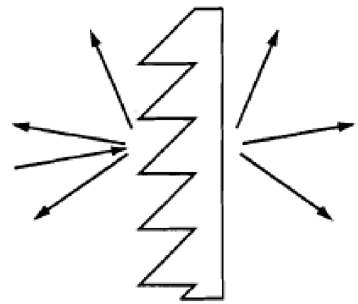
RECTANGULAR GR.
BINARY GR.
LAMELLAR GR.



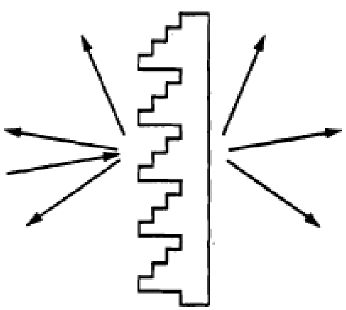
SINUSOIDAL GR.



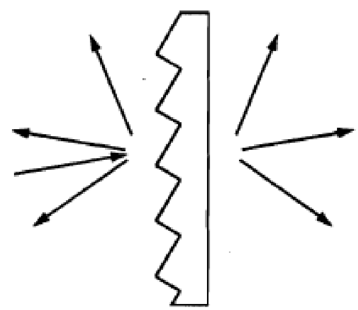
THREE-LEVEL GR.



SAWTOOTH GR.
BLAZED GR.



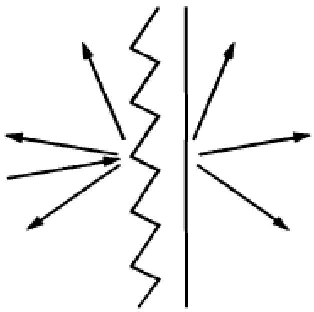
STAIRSTEP GR.
MULTILEVEL GR.
BINARY MASK GR.



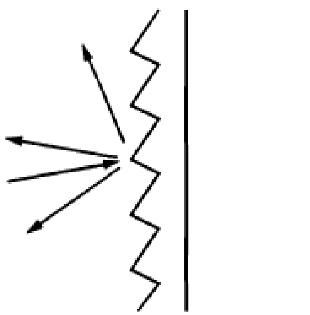
ECHLETTE GR.

Grating Classification

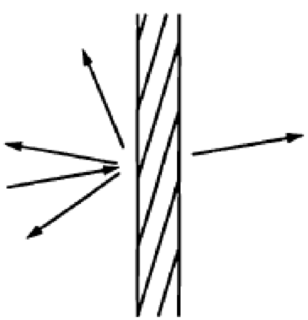
Transmission or Reflection



DIELECTRIC TRANSMISSION GRATING

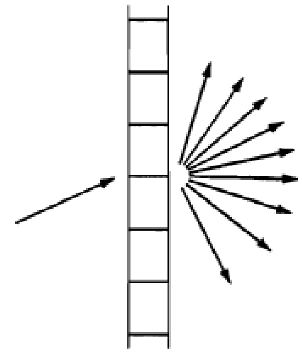


METALLIC REFLECTION GRATING

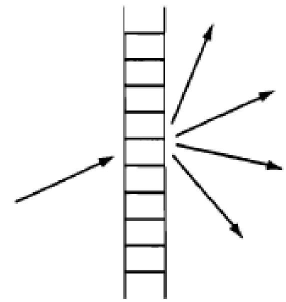


DIELECTRIC REFLECTION GRATING

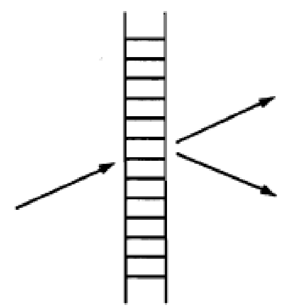
Classification based on Regime



RAMAN-NATH REGIME



INTERMEDIATE REGIME



BRAGG REGIME

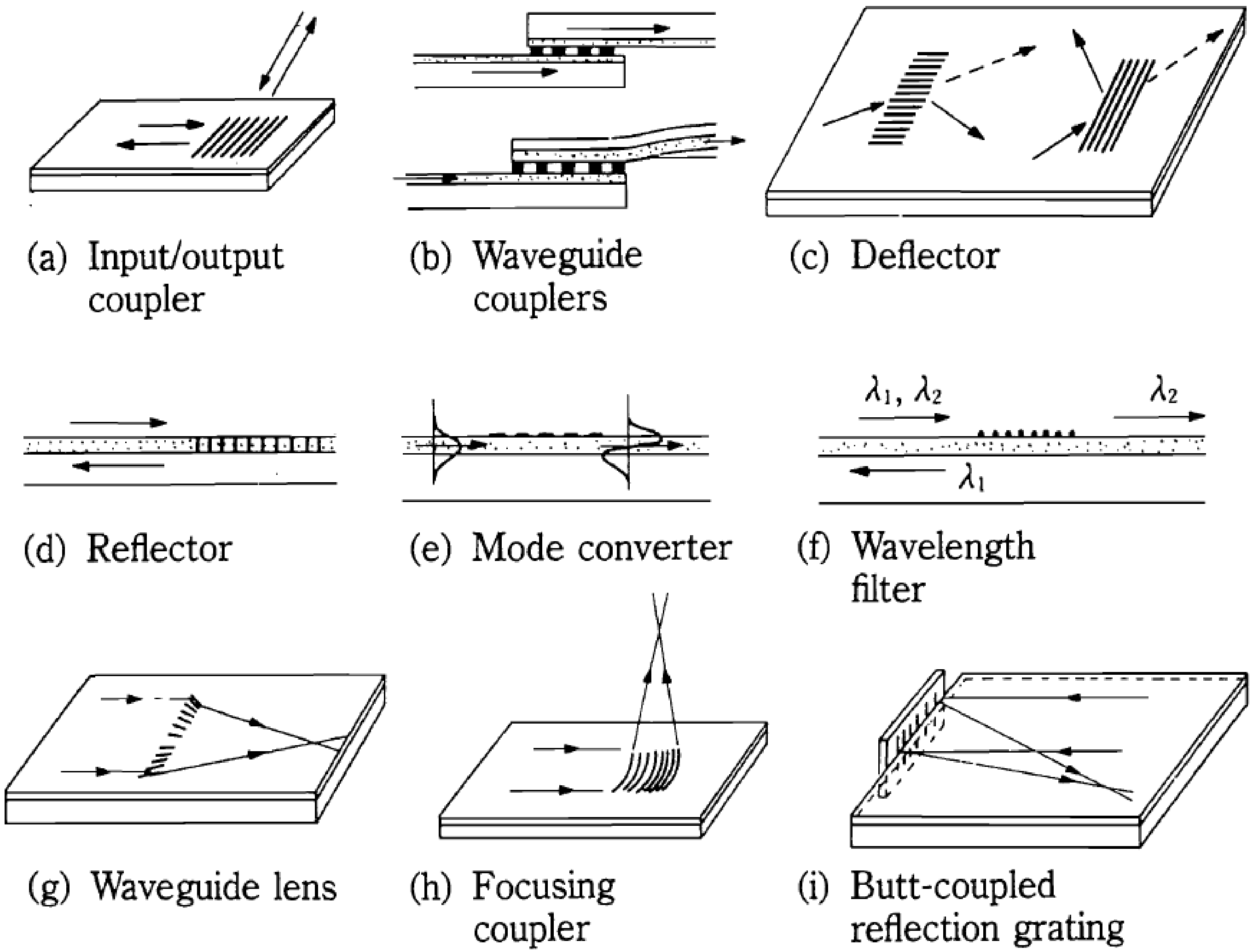
Diffraction By Gratings

- Acousto-Optics
- Diffractive Optics
- Integrated Optics
- Holography
- Optical Computing
- Optical Signal Processing
- Spectroscopy

Grating Applications

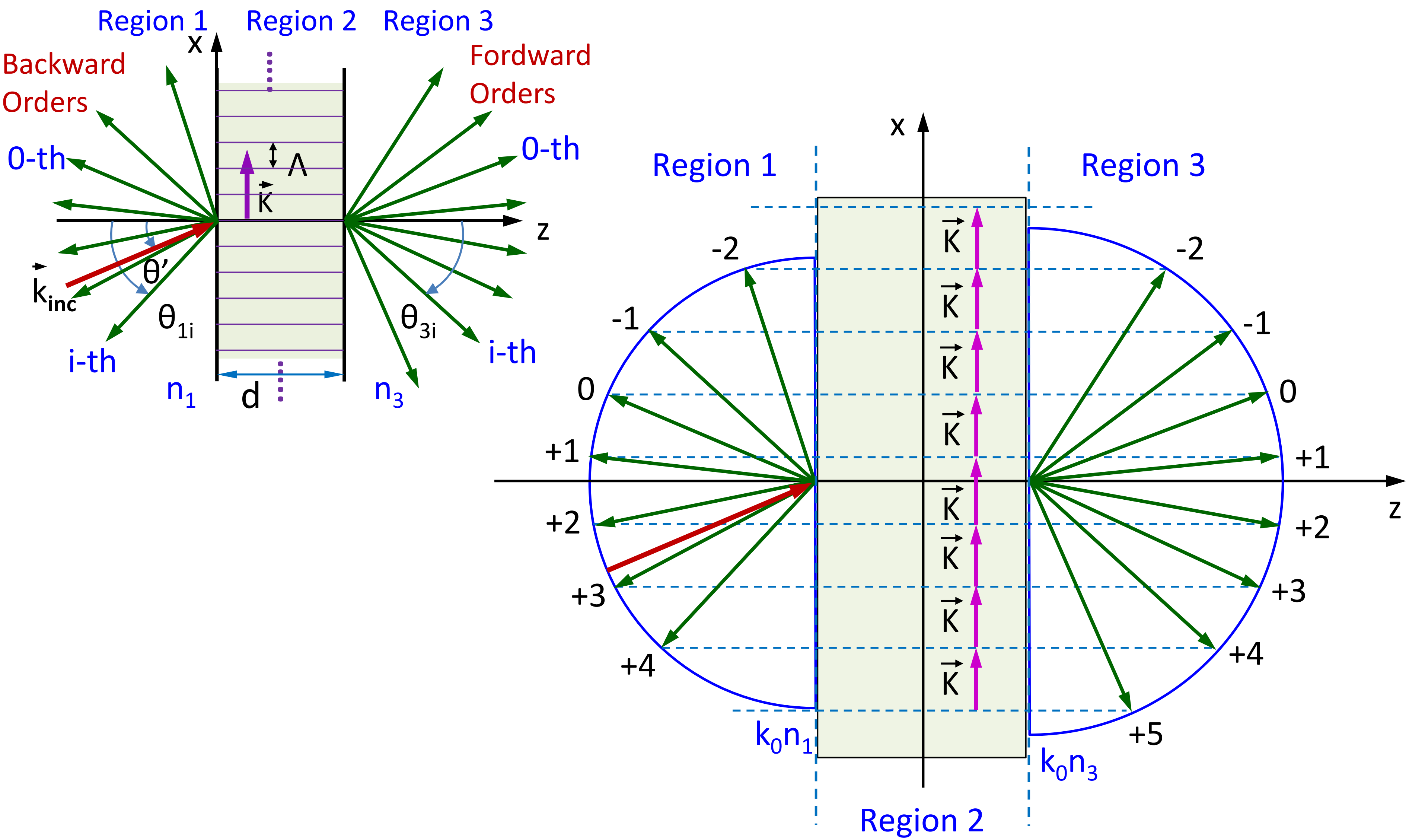
- Acoustic-Wave Generation
- Antireflection Surfaces
- Beam Coding, Coupling, Detection, etc.
- Grating Lenses
- Grating Scanners
- Head-Up Displays
- Holographic Optical Elements
- Interferometry
- Instrumentation
- Mode Conversion
- Multiplexing / Demultiplexing
- Modulation / Switching
- Optical Interconnections
- Photonic Crystal Devices
- Spectral Analysis

Grating Applications In Integrated Optics

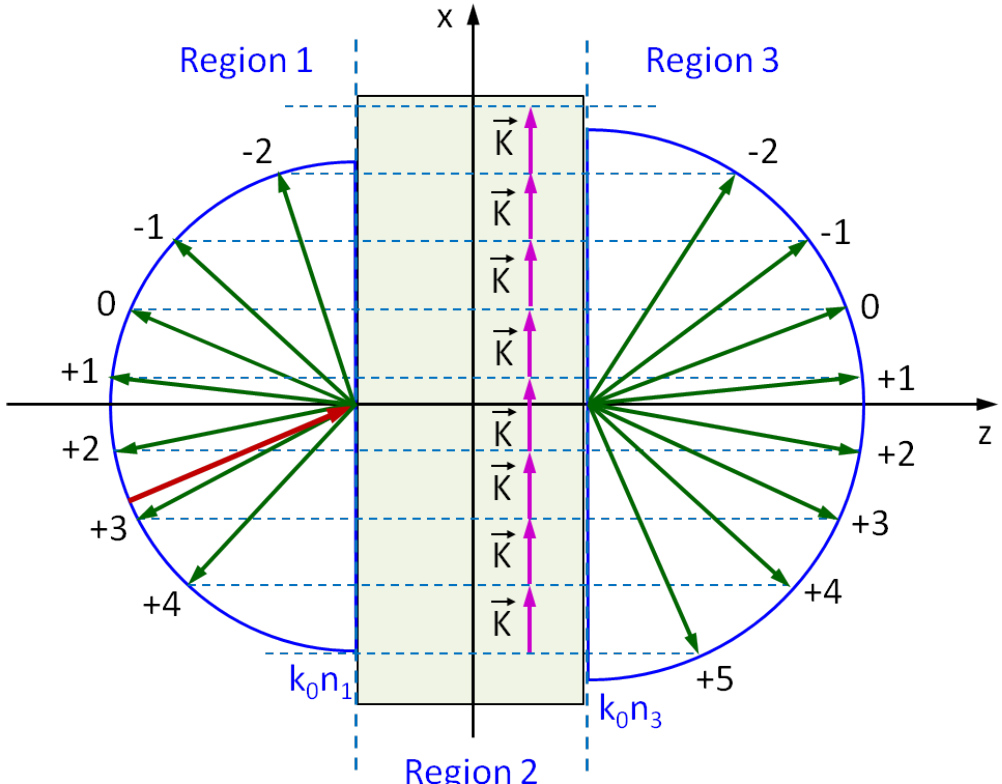


From “Optical Integrated Circuits”, Nishihara, Haruna, and Suhara, McGraw-Hill 1989

Floquet Condition



Grating Equation



FORWARD-DIFFRACTED ORDERS

$$n_1 \sin\theta' - n_3 \sin\theta_i'' = i\frac{\lambda}{\Lambda}$$

BACKWARD-DIFFRACTED ORDERS

$$\sin\theta' + \sin\theta_i' = i\frac{\lambda}{\Lambda n_1}$$

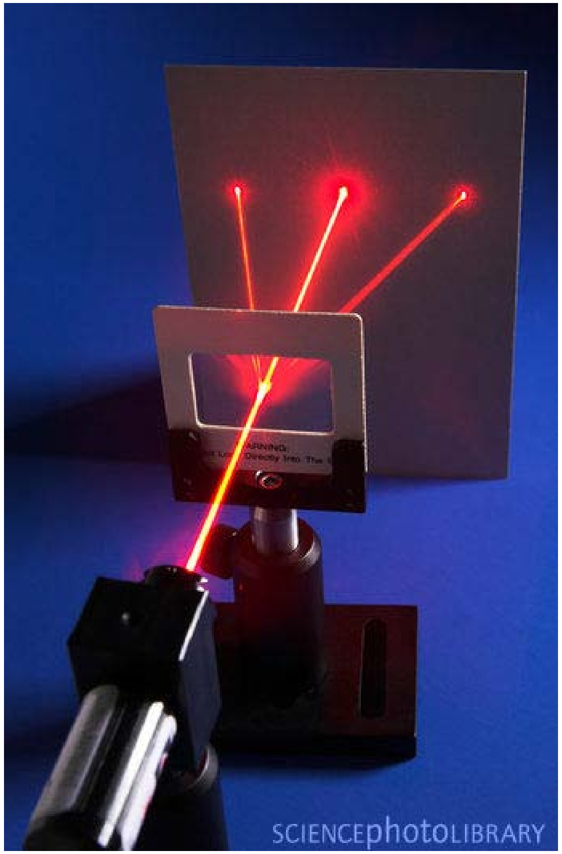
θ' = angle of incidence

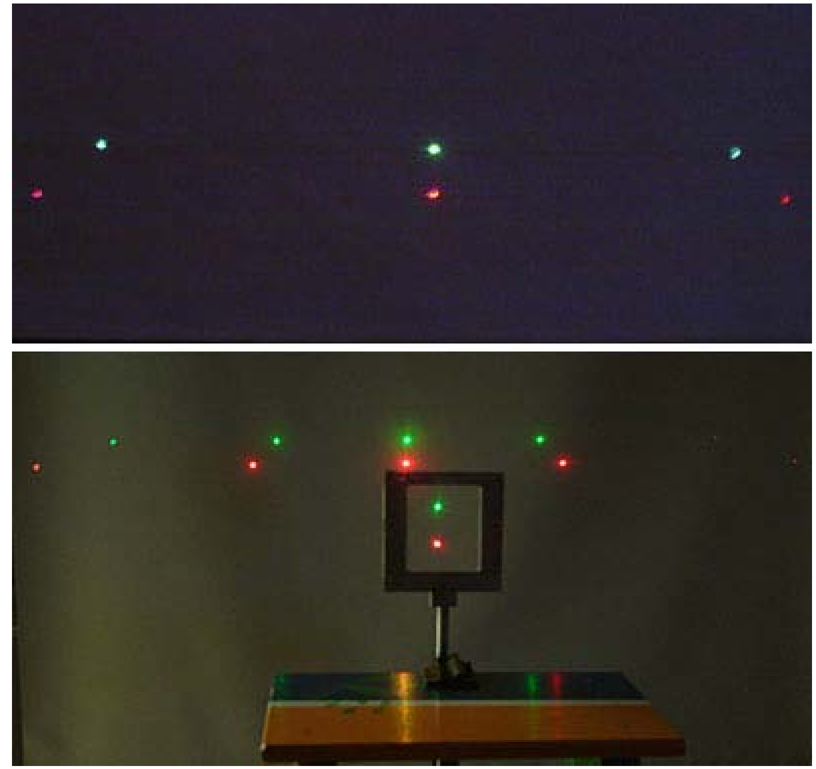
θ_i'' = angle of forward diffraction

θ_i' = angle of backward diffraction

All are measured CCW from the normal in their respective regions.

Grating Equation





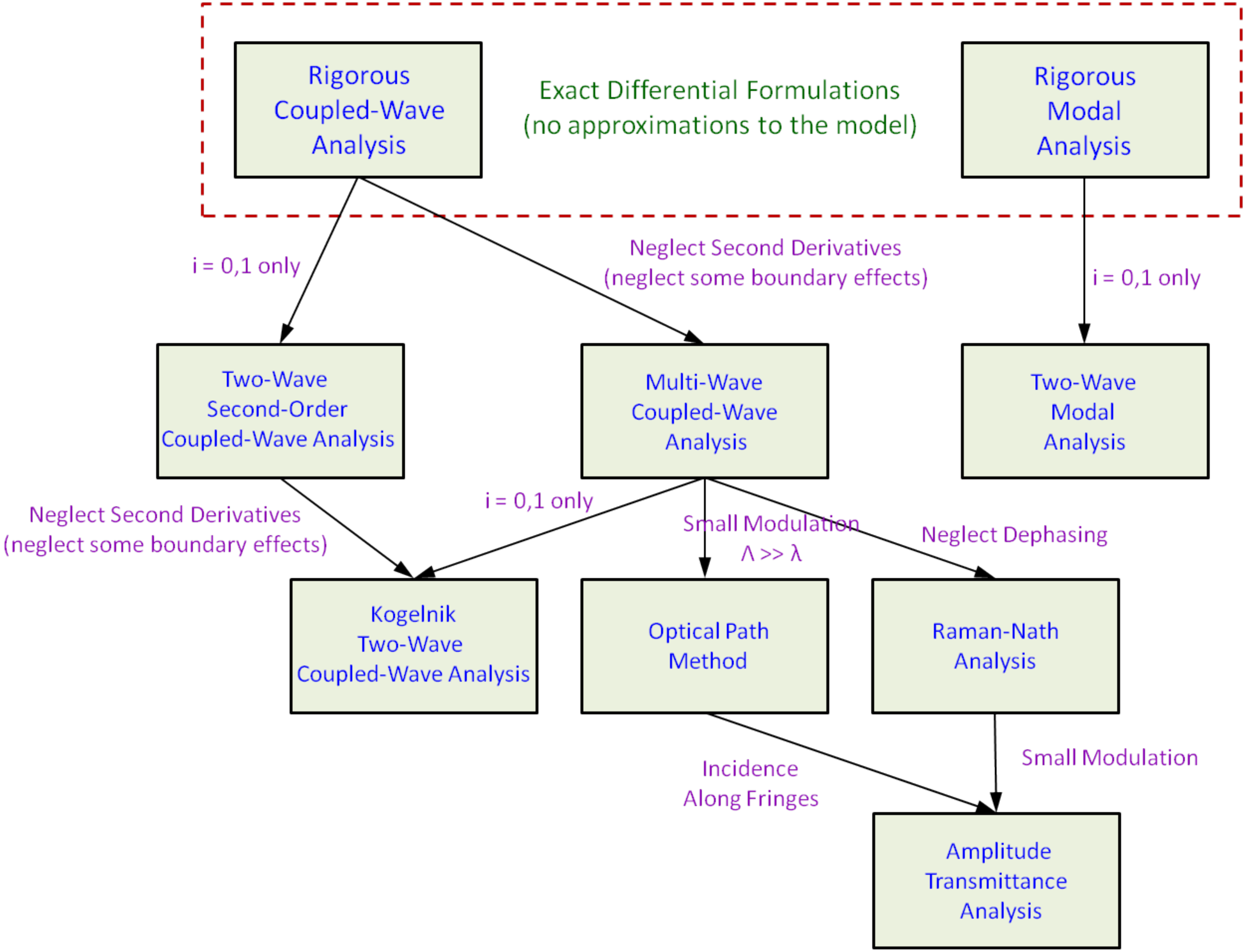
Red laser beam split by a diffraction grating. Transmission diffraction gratings consist of many thin lines of either absorptive material or thin grooves on an otherwise transparent substrate. Light transmission through a diffraction grating occurs along discrete directions, called diffraction orders. Here a diode laser beam (635 nm) is split into three diffraction orders (+1, 0, -1). This grating's groove density is 500 lines/mm.

http://www.sciencephoto.com/media/92635/view

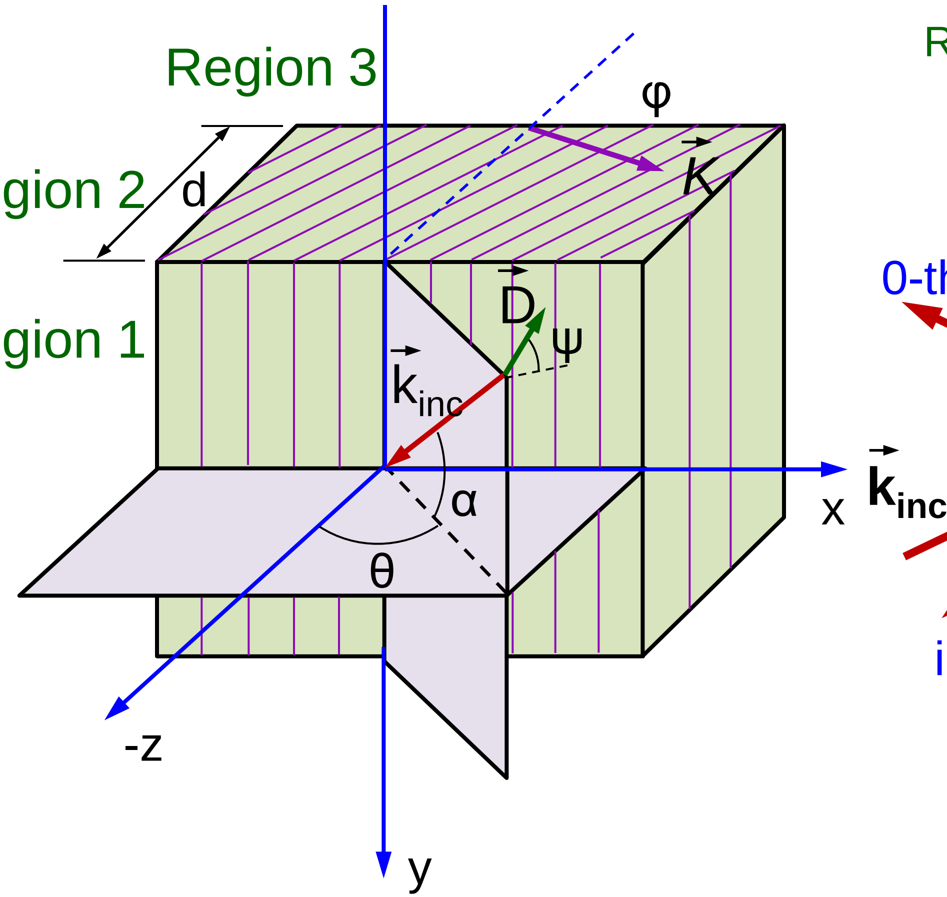
Methods Of Analysis Of Gratings

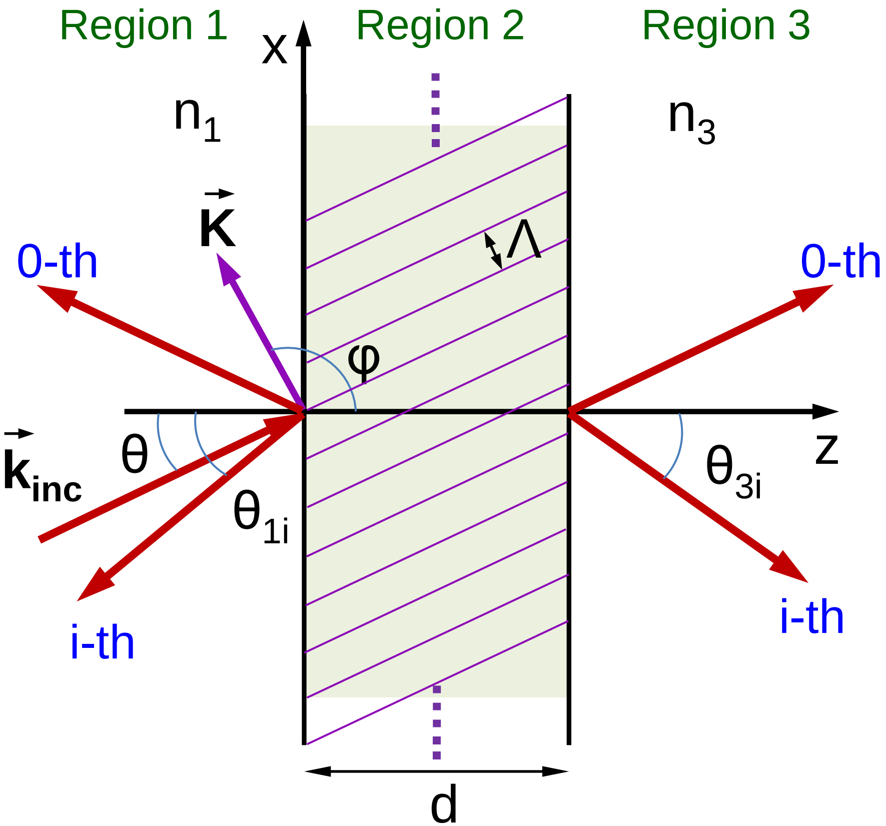
- Integral Methods
  - Finite Elements
  - Boundary Elements
- Differential Methods
  - Exact Methods
    - Rigorous Coupled Wave Analysis (RCWA)
    - Modal Analysis
  - Approximate Methods
    - Two-Wave Coupled-Wave Analysis (Kogelnik's)
    - Raman-Nath Analysis
    - Others

Differential Grating Diffraction Analysis Hierarchy



Holographic Grating Diffraction Geometry





Electromagnetic Problem Formulation

Maxwell Equations

$$\vec{\nabla} \times \vec{E} = -j\omega\vec{B}$$

$$\vec{\nabla} \times \vec{H} = +j\omega\vec{D} + \vec{J}$$

Constitutive Relations

$$\vec{D} = \epsilon_0 \tilde{\varepsilon} \vec{E}$$

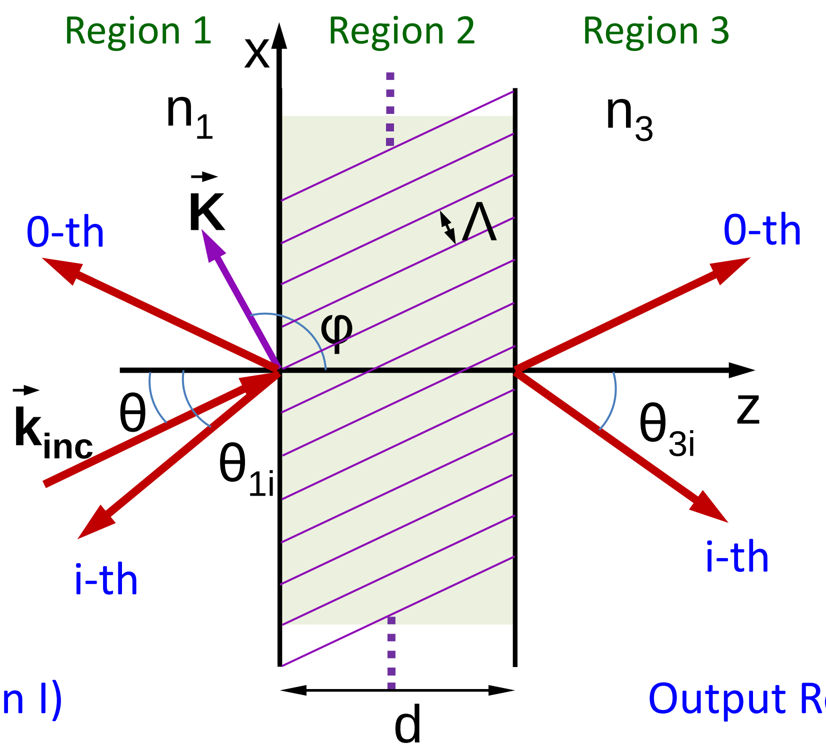
$$\vec{B} = \mu_0 \vec{H}$$

$$\vec{J} = \tilde{\sigma} \vec{E}$$

Medium Properties: Permittivity, Conductivity Tensors are Periodic

Electromagnetic Boundary Conditions: Continuity of Tangential Electric and Magnetic Field Components

Electromagnetic Field Expansions
Rigorous Coupled Wave Analysis (RCWA)



Input Region (Region I)

$$\vec{E}_I = \vec{E}_{inc} + \sum_i \vec{R}_i \exp[-j\vec{k}_{1i} \cdot \vec{r}]$$

$$\vec{H}_I = -\frac{1}{j\omega\mu_0}\vec{\nabla} \times \vec{E}_I$$

Output Region (Region III)

$$\vec{E}_{III} = \sum_i \vec{T}_i \exp[-j\vec{k}_{3i} \cdot \vec{r}]$$

$$\vec{H}_{III} = -\frac{1}{j\omega\mu_0}\vec{\nabla} \times \vec{E}_{III}$$

Electromagnetic Field Expansions
Rigorous Coupled Wave Analysis (RCWA)

Grating Region (Region II)

$$\vec{E}_{II} = \sum_i \vec{S}_i(z) \exp[-j\vec{\sigma}_i \cdot \vec{r}] = \sum_i \vec{S}_i(z) \exp[-j(\vec{k}_{inc} - i\vec{K}) \cdot \vec{r}]$$

$$\vec{H}_{II} = \left(\frac{\epsilon_0}{\mu_0}\right)^{1/2} \sum_i \vec{U}_i(z) \exp[-j\vec{\sigma}_i \cdot \vec{r}] = \left(\frac{\epsilon_0}{\mu_0}\right)^{1/2} \sum_i \vec{U}_i(z) \exp[-j(\vec{k}_{inc} - i\vec{K}) \cdot \vec{r}]$$

Complex Permittivity Tensor Expansions (Region II)

$$\tilde{\varepsilon} = \sum_h \tilde{\varepsilon}_h \exp[jh\vec{K} \cdot \vec{r}]$$

$$\tilde{\varepsilon}_h = [\tilde{\varepsilon} - j\tilde{\sigma}/\omega\epsilon_0]_h = \text{Fourier Tensor Component}$$

Rigorous Coupled Wave Analysis (RCWA) Numerical Implementation

Truncation to Arbitrary Number of Diffraction Orders: *M =2m+1*

Grating Region Equations

$$\frac{d\tilde{V}}{dz} = j\tilde{A}\tilde{V}$$

$$\tilde{V}^T = [\tilde{S}_x^T, \tilde{S}_y^T, \tilde{U}_x^T, \tilde{U}_y^T] \quad (4M \times 1)$$

$$\tilde{A} = \text{Coupling Matrix} \quad (4M \times 4M)$$

Standard Eigenvector/Eigenvalue Analysis

$$\tilde{V}(z) = \tilde{W} \exp[\tilde{\Lambda} z]\tilde{C}$$

$$\tilde{W} = \text{Matrix of Eigenvectors of } \tilde{A} \quad (4M \times 4M)$$

$$\tilde{\Lambda} = \text{Matrix of Eigenvalues (diagonal) of } \tilde{A} \quad (4M \times 4M)$$

$$\tilde{C} = \text{Vector of Unknown Coefficients} \quad (4M \times 1)$$

Boundary Conditions: Input and Output Regions Boundaries

Rigorous Coupled Wave Analysis (RCWA) Numerical Implementation

Number of Unknowns = 10*M*

$\vec{R}_i$	(Region I)	3*M*
$\vec{T}_i$	(Region III)	3*M*
$\tilde{C}$	(Region III)	4*M*

Number of Equations = 10*M*

Boundary Conditions (Regions I-II and II-III) 4*M*+4*M* = 8*M*

$\vec{k}_{1i} \cdot \vec{R}_i = 0$	Region I Plane Waves	*M*
$\vec{k}_{3i} \cdot \vec{T}_i = 0$	Region III Plane Waves	*M*

Rigorous Coupled Wave Analysis (RCWA)
Numerical Implementation

System of Linear Equations (10M x 10M)

$$\tilde{L}\tilde{x} = \tilde{b}$$

$$\tilde{L} = \text{Matrix of Coefficients of Linear Equations} \quad (10M \times 10M)$$

$$\tilde{x}^T = [\vec{R}_i^T, \vec{T}_i^T, \tilde{C}^T] \quad (10M \times 1)$$

$$\tilde{b} = \text{Excitation Vector (depends on Incident Wave)} \quad (10M \times 1)$$

Size of Linear System can be Reduced

Rigorous Coupled Wave Analysis (RCWA)
Diffraction Efficiencies

Efficiencies of Backward-Diffracted Waves

$$DE_{1i} = -\frac{\mathcal{R}e\{k_{1iz}^*\}}{k_{inc,z}} |\vec{R}_i|^2$$

Efficiencies of Forward-Diffracted Waves

$$DE_{3i} = +\frac{\mathcal{R}e\{k_{3iz}^*\}}{k_{inc,z}} |\vec{T}_i|^2$$

For Lossless Gratings

$$\sum_i \{DE_{1i} + DE_{3i}\} = 1$$

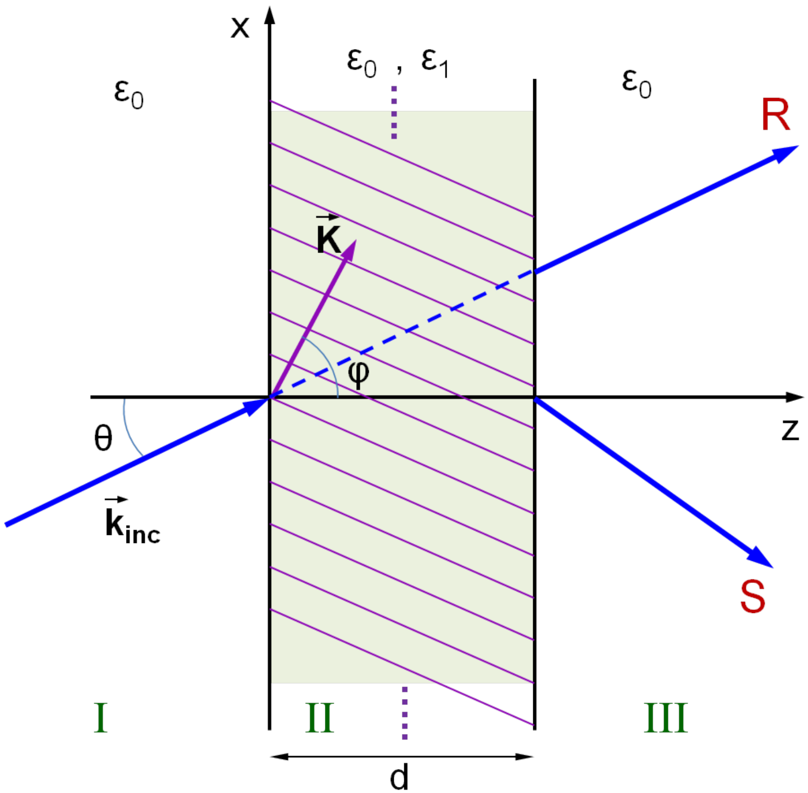
Rigorous Coupled Wave Analysis (RCWA) Generalizations

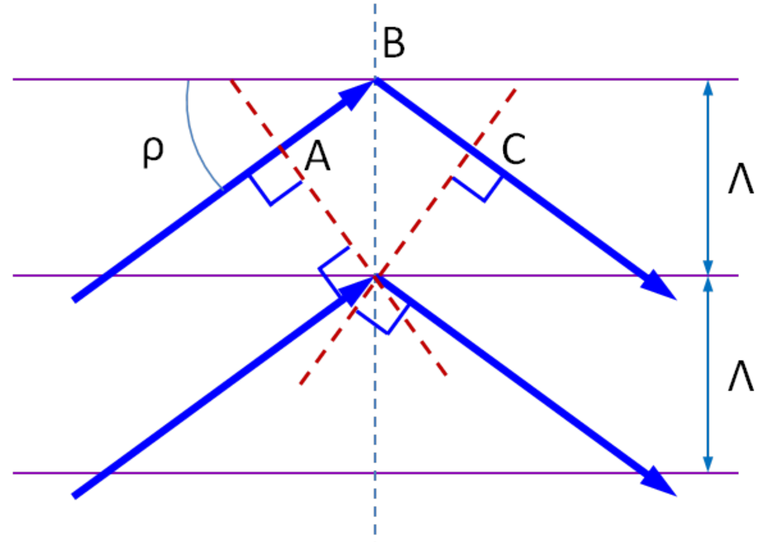
- Generalized Media (in terms of constitutive equations)

$$\vec{D} = \epsilon_0 \tilde{\varepsilon} \vec{E} + \tilde{g} \vec{H}$$
$$\vec{B} = \tilde{h} \vec{E} + \mu_0 \tilde{\mu} \vec{H}$$

- Multiple Cascaded Gratings
- Surface-Relief Gratings
- Varying Modulation Gratings
- Multiplexed Gratings
- Biaxial Input and/or Output Regions

Bragg Condition





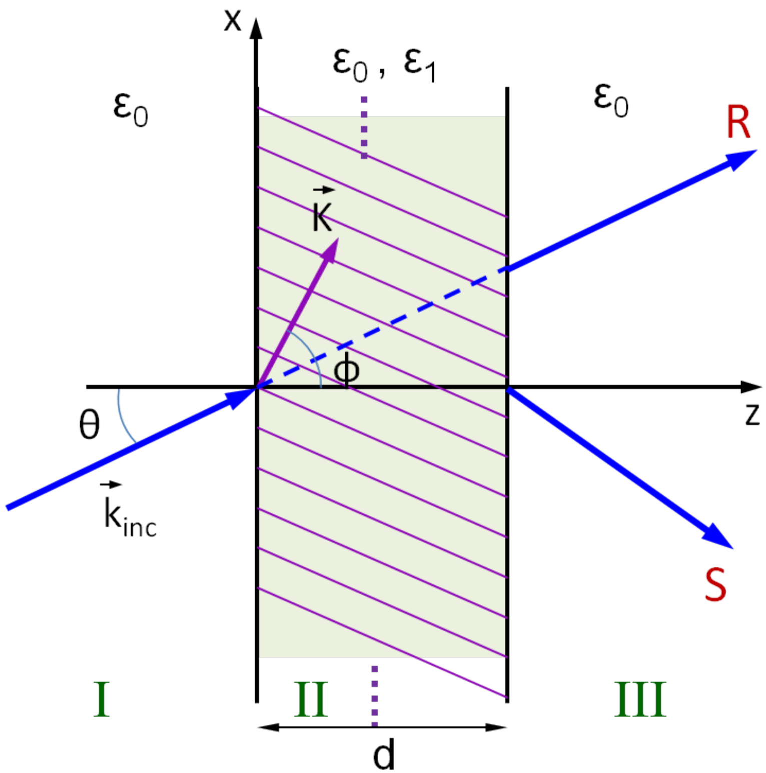
$$k_0 n_0 (AB + BC) = m 2\pi \implies$$

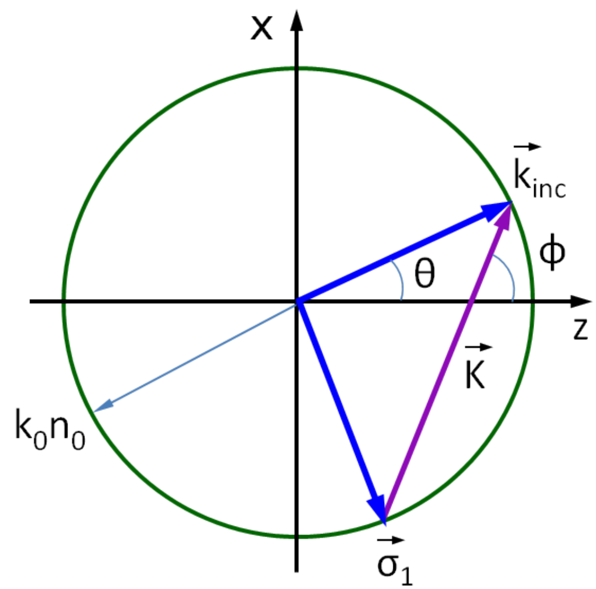
$$\boxed{2\Lambda \sin(\rho) = m \left(\frac{\lambda_0}{n_0} \right)}$$

$$\rho = \frac{\pi}{2} - (\phi - \theta) \implies$$

$$\boxed{2\Lambda \cos(\phi - \theta) = m \left(\frac{\lambda_0}{n_0} \right)}$$

Bragg Condition





$$\vec{\sigma}_i \cdot \vec{\sigma}_i = k_0^2 n_0^2$$

$$\left(\vec{k}_{inc} - i\vec{K}\right) \cdot \left(\vec{k}_{inc} - i\vec{K}\right) = k_0^2 n_0^2$$

$$\vec{k}_{inc} \cdot \vec{k}_{inc} - 2i\vec{K} \cdot \vec{k}_{inc} + i^2 \vec{K} \cdot \vec{K} = k_0^2 n_0^2$$

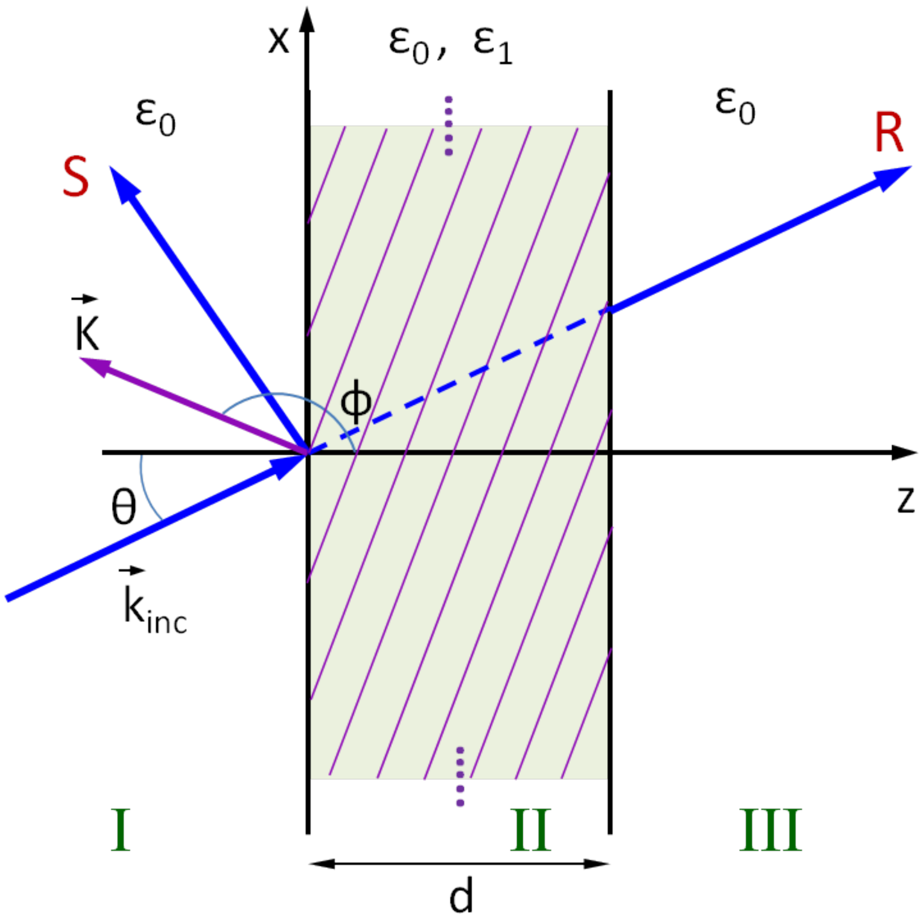
$$\boxed{i\vec{K} \cdot \vec{k}_{inc} = i^2 \vec{K} \cdot \vec{K}}$$

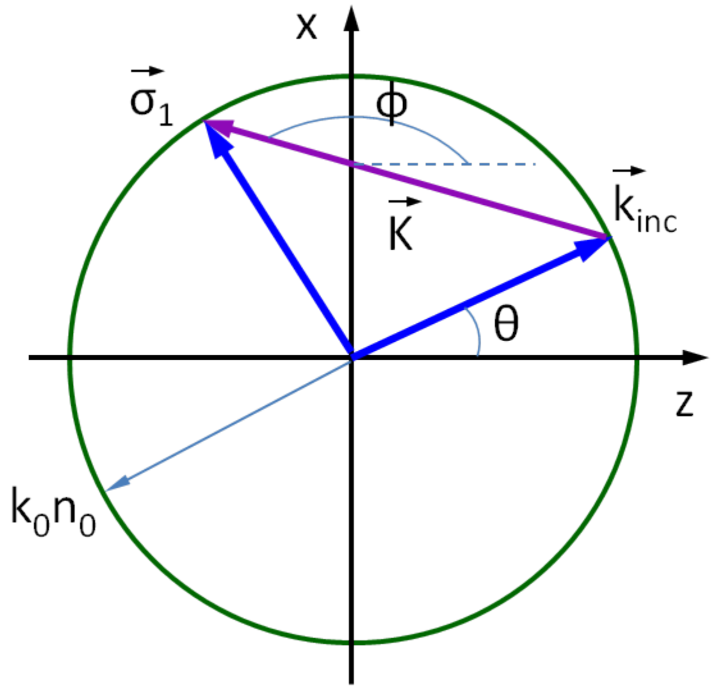
$$\vec{K} = \frac{2\pi}{\Lambda}\left(\sin\phi\hat{x} + \cos\phi\hat{z}\right)$$

$$\vec{k}_{inc} = k_0 n_0 \left(\sin\theta\hat{x} + \cos\theta\hat{z}\right)$$

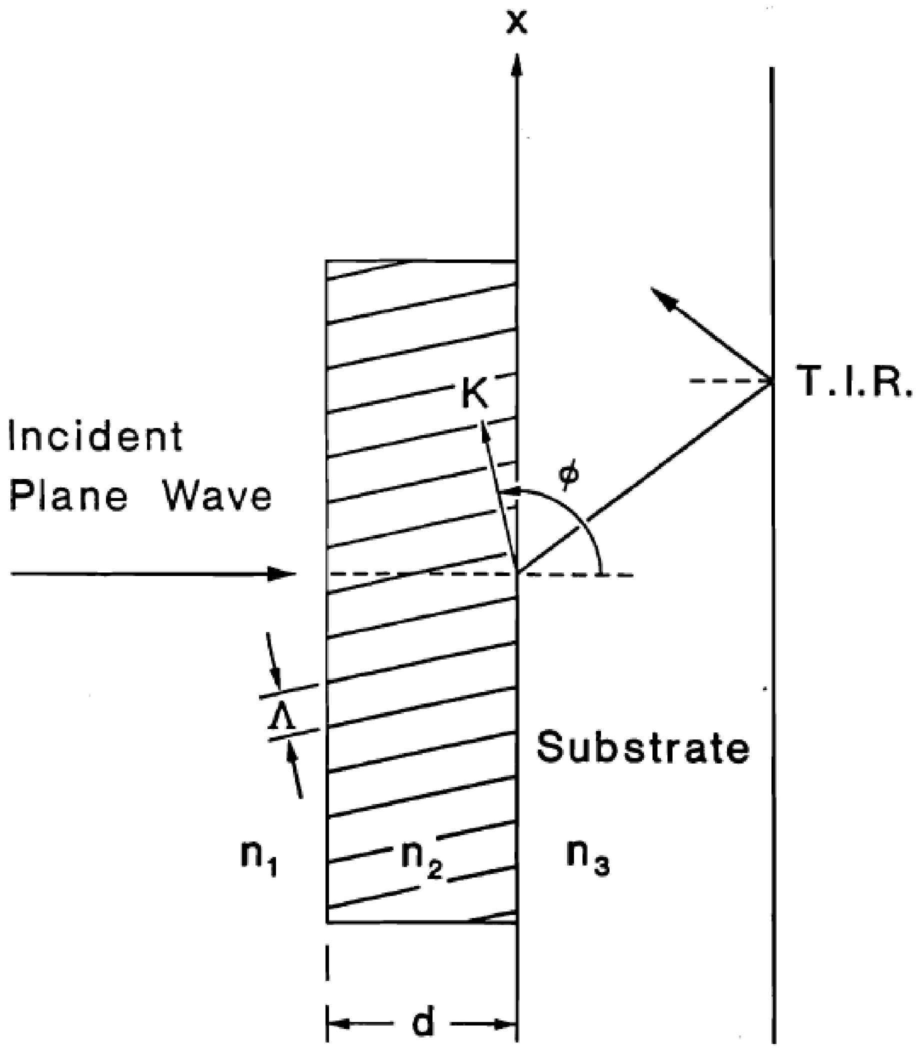
$$\boxed{2\Lambda\cos(\phi - \theta) = i\left(\frac{\lambda_0}{n_0}\right)}$$

Bragg Condition (Reflection Grating)

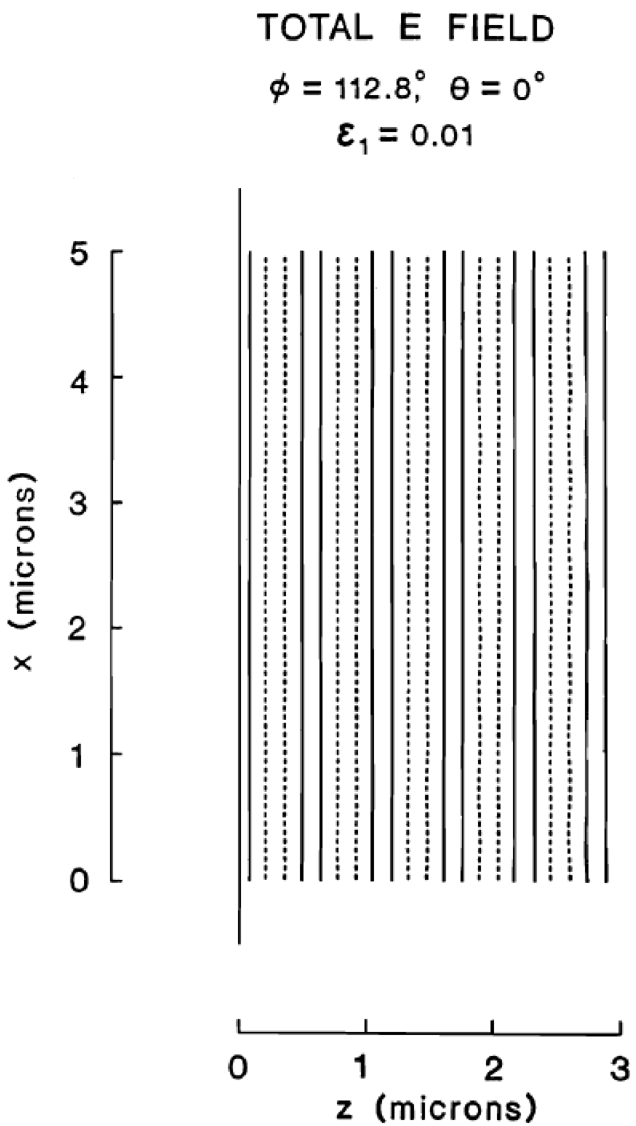


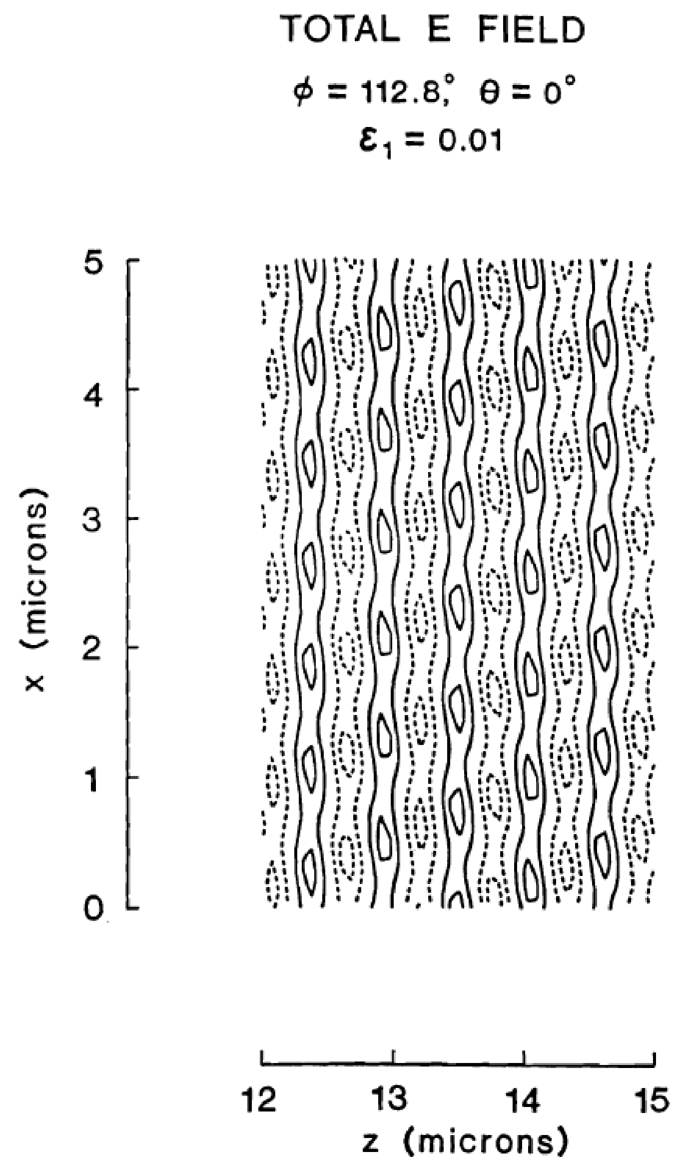


Rigorous Coupled Wave Analysis (RCWA)
Diffractive Optical Interconnect

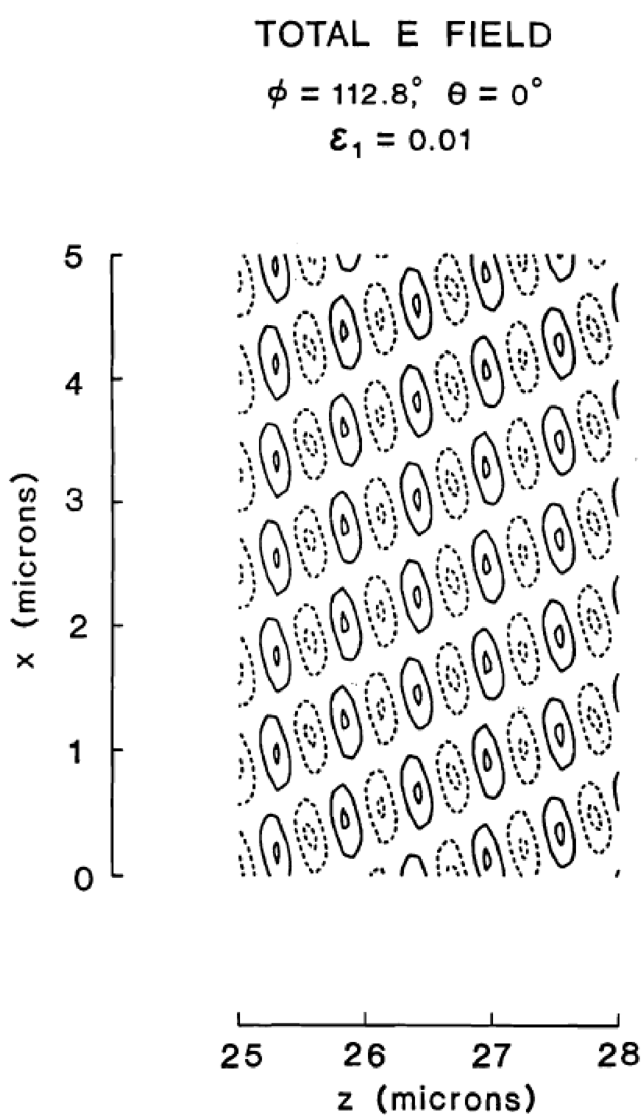


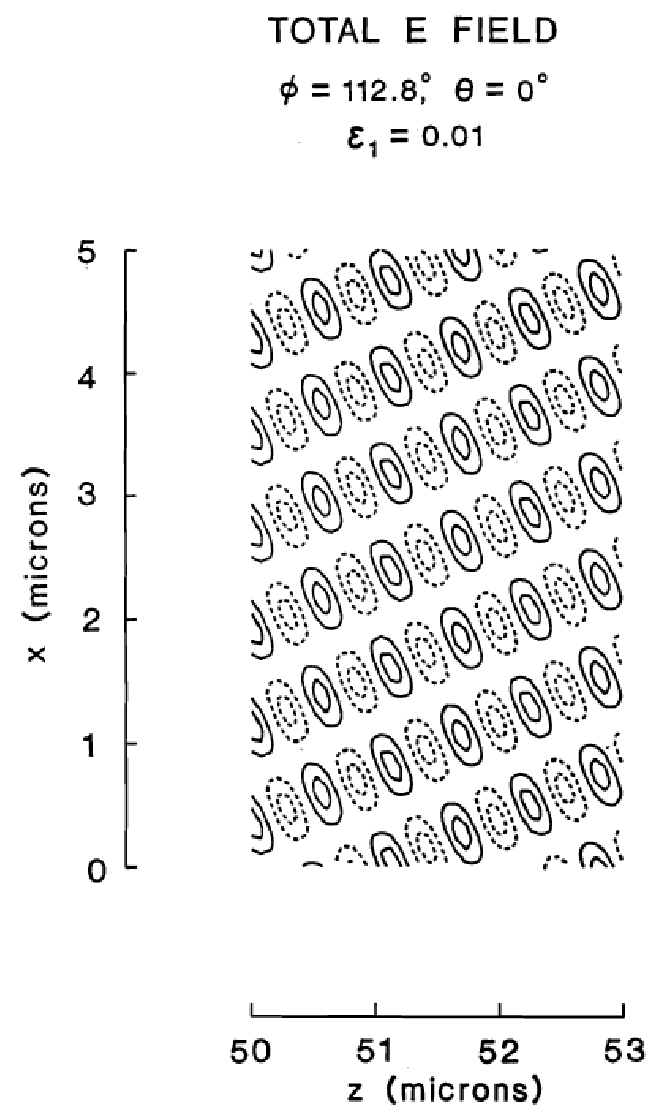
Rigorous Coupled Wave Analysis (RCWA)
Diffractive Optical Interconnect



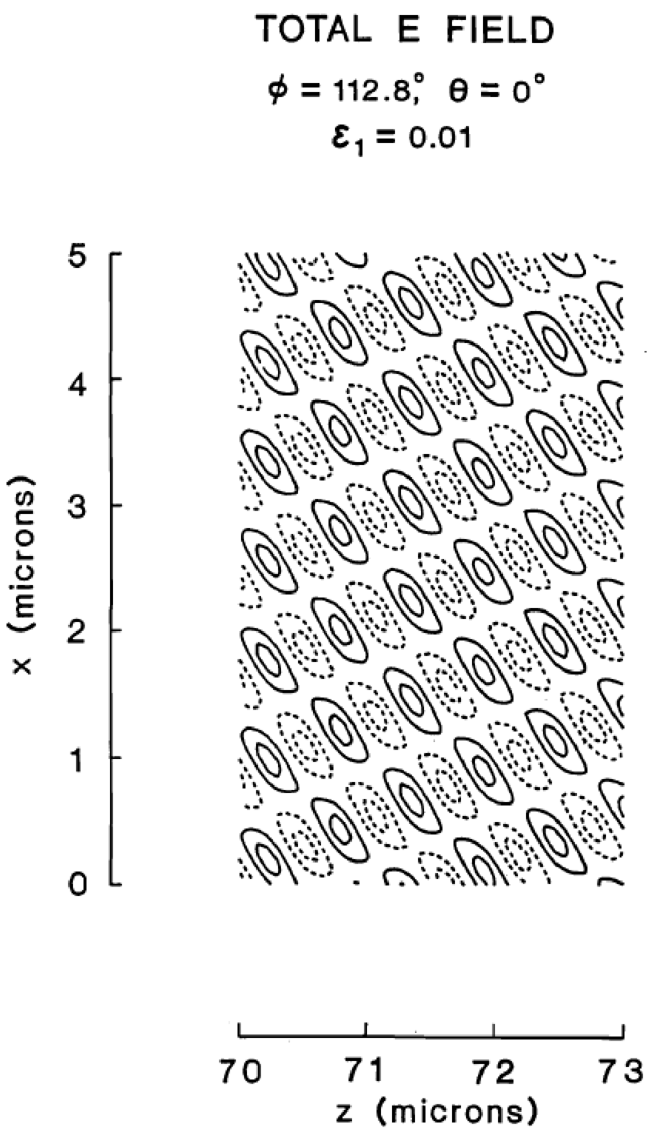


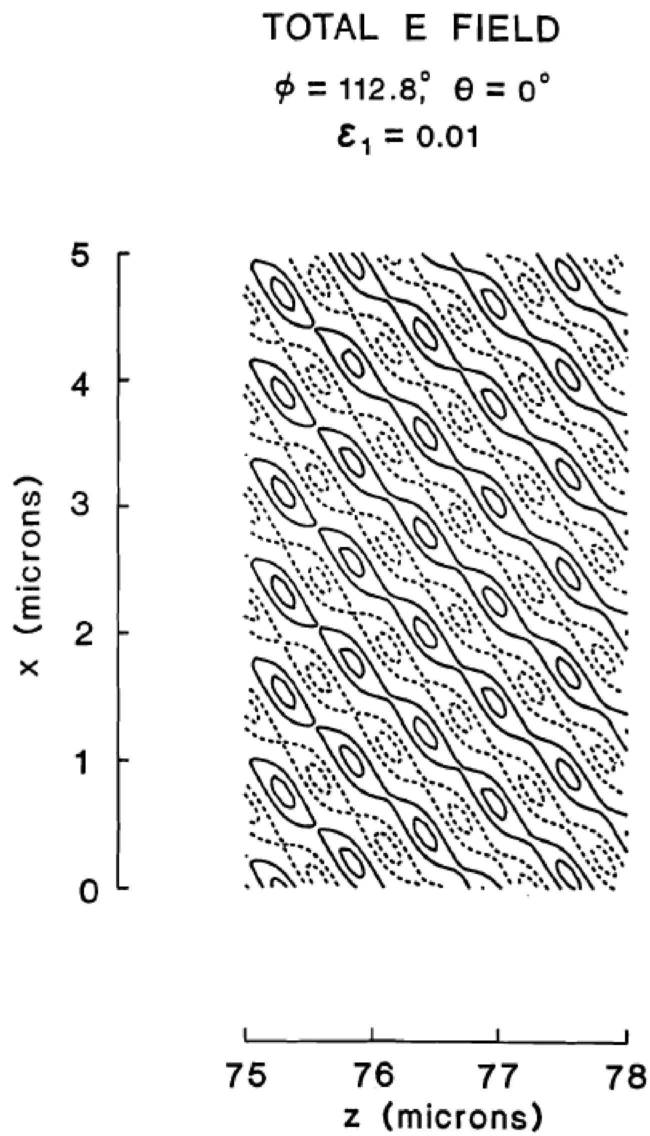
Rigorous Coupled Wave Analysis (RCWA)
Diffractive Optical Interconnect



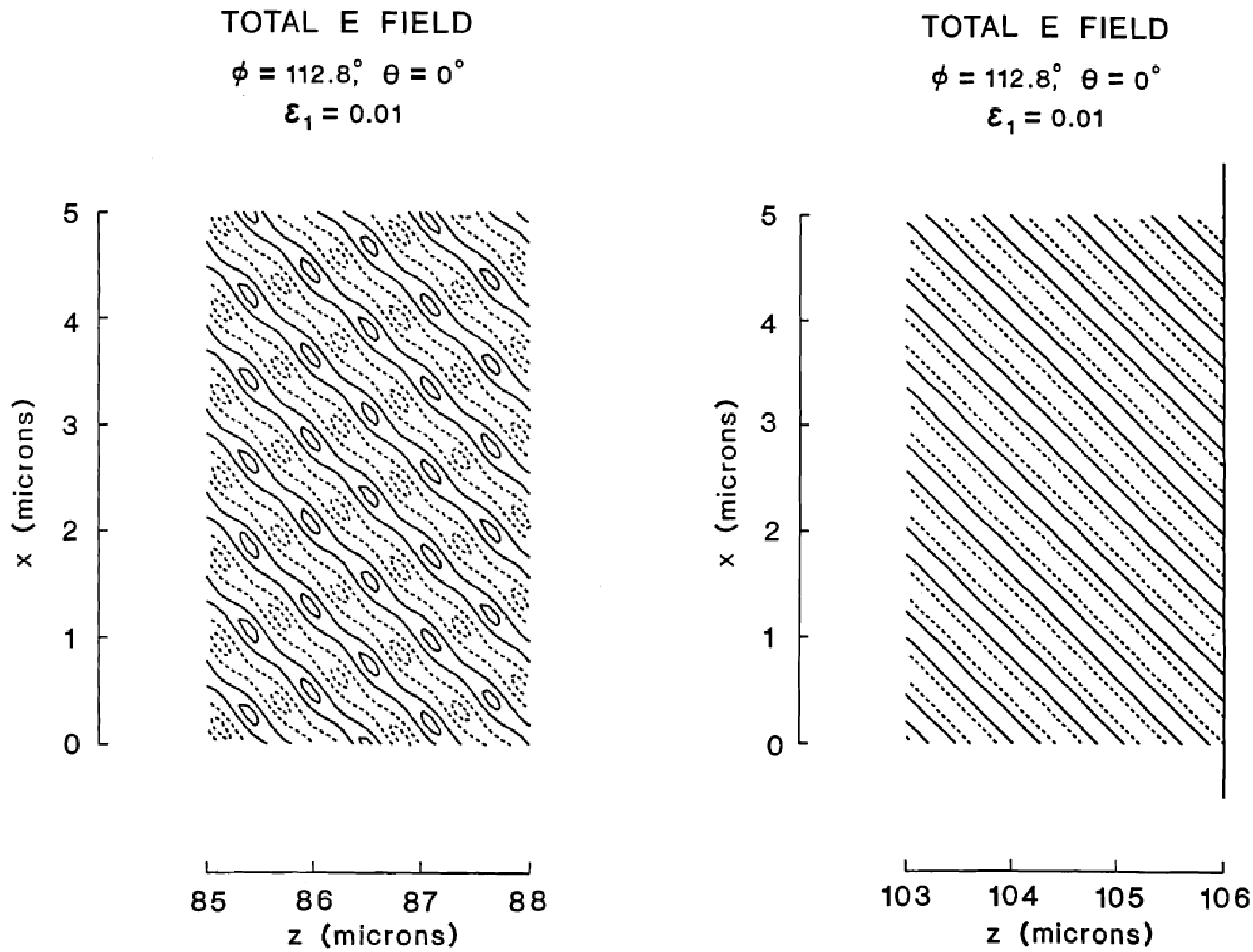


Rigorous Coupled Wave Analysis (RCWA)
Diffractive Optical Interconnect

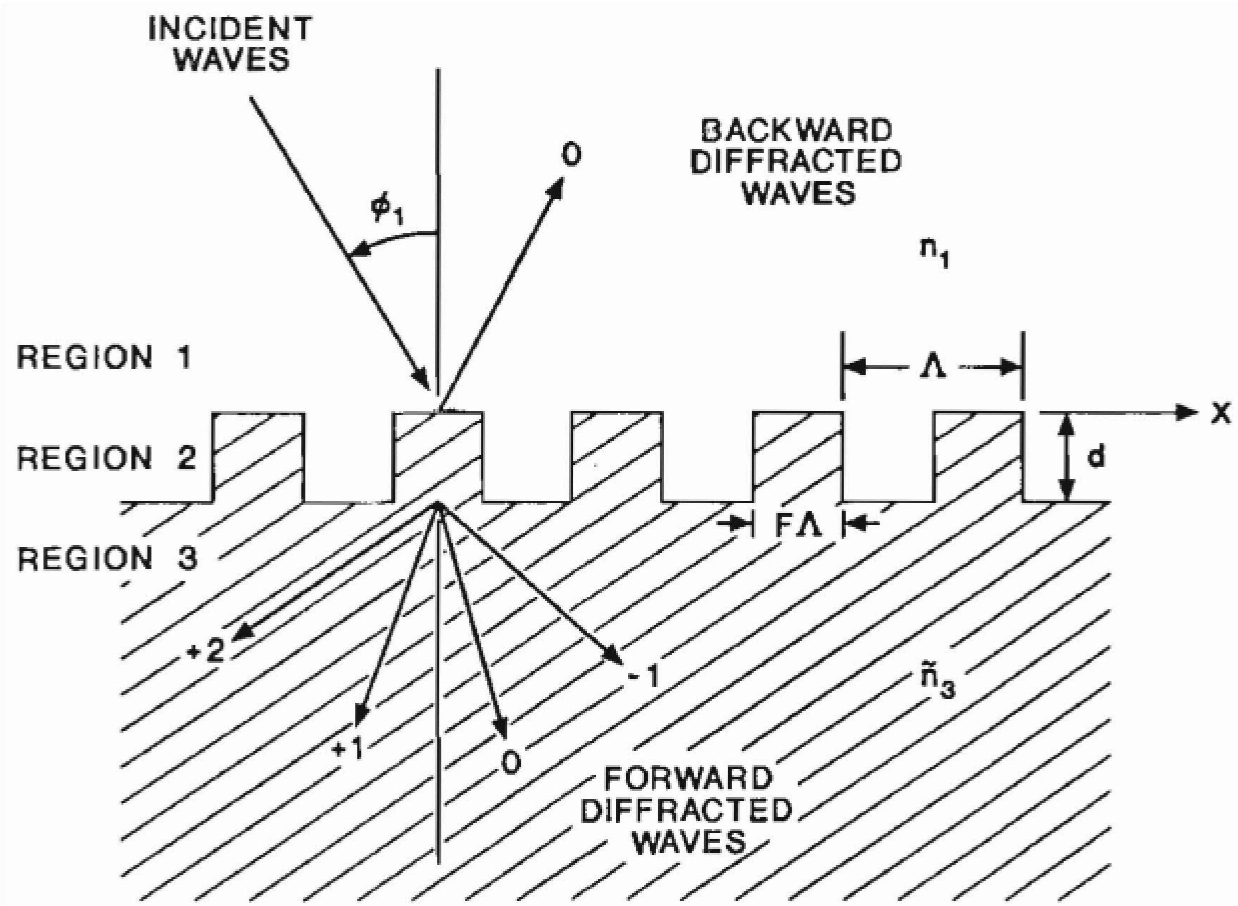




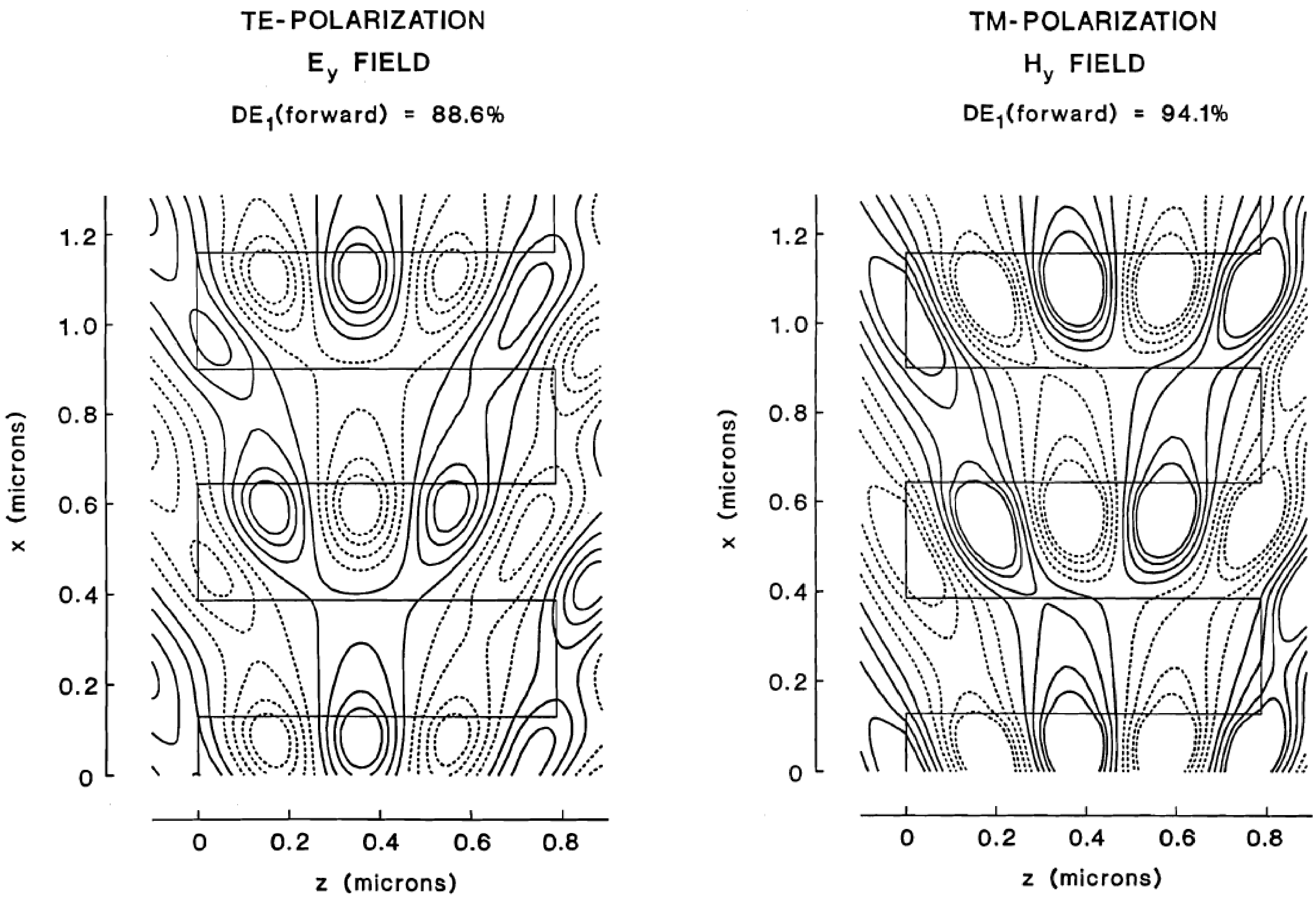
Rigorous Coupled Wave Analysis (RCWA)
Diffractive Optical Interconnect



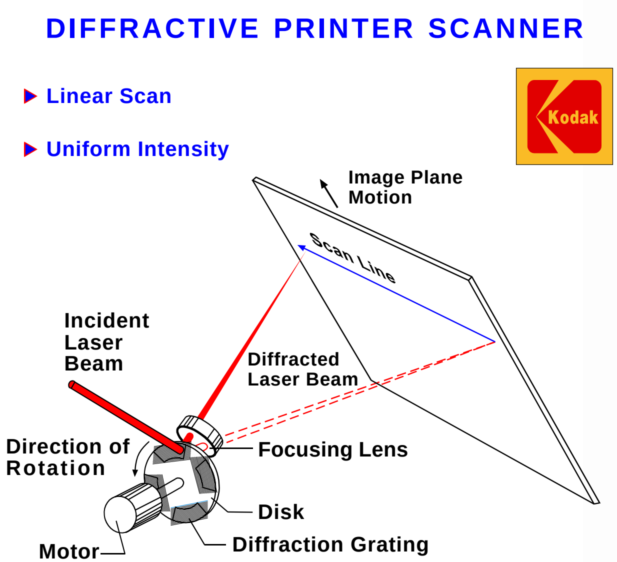
Rigorous Coupled Wave Analysis (RCWA)
Surface-Relief Grating

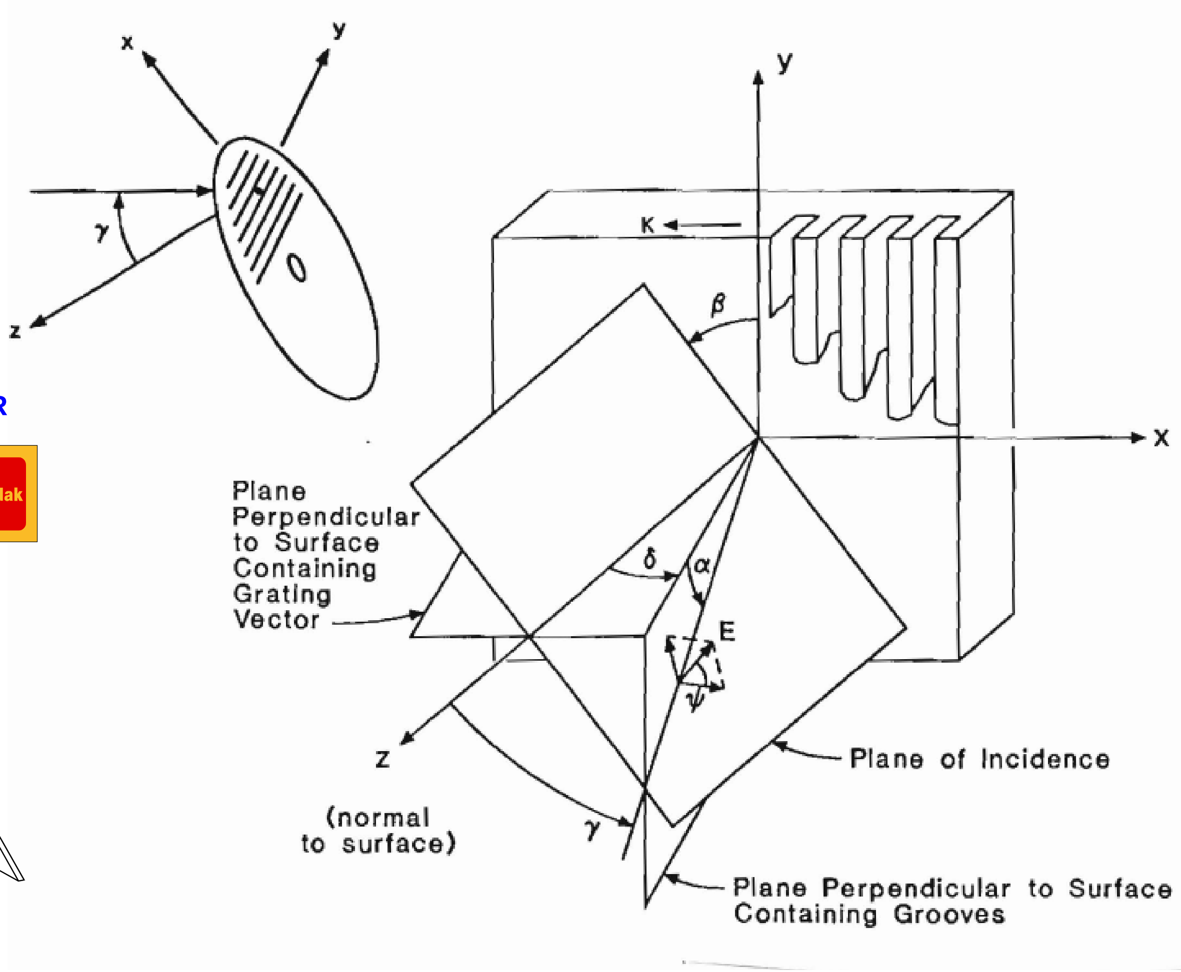


Rigorous Coupled Wave Analysis (RCWA)
Surface-Relief Grating

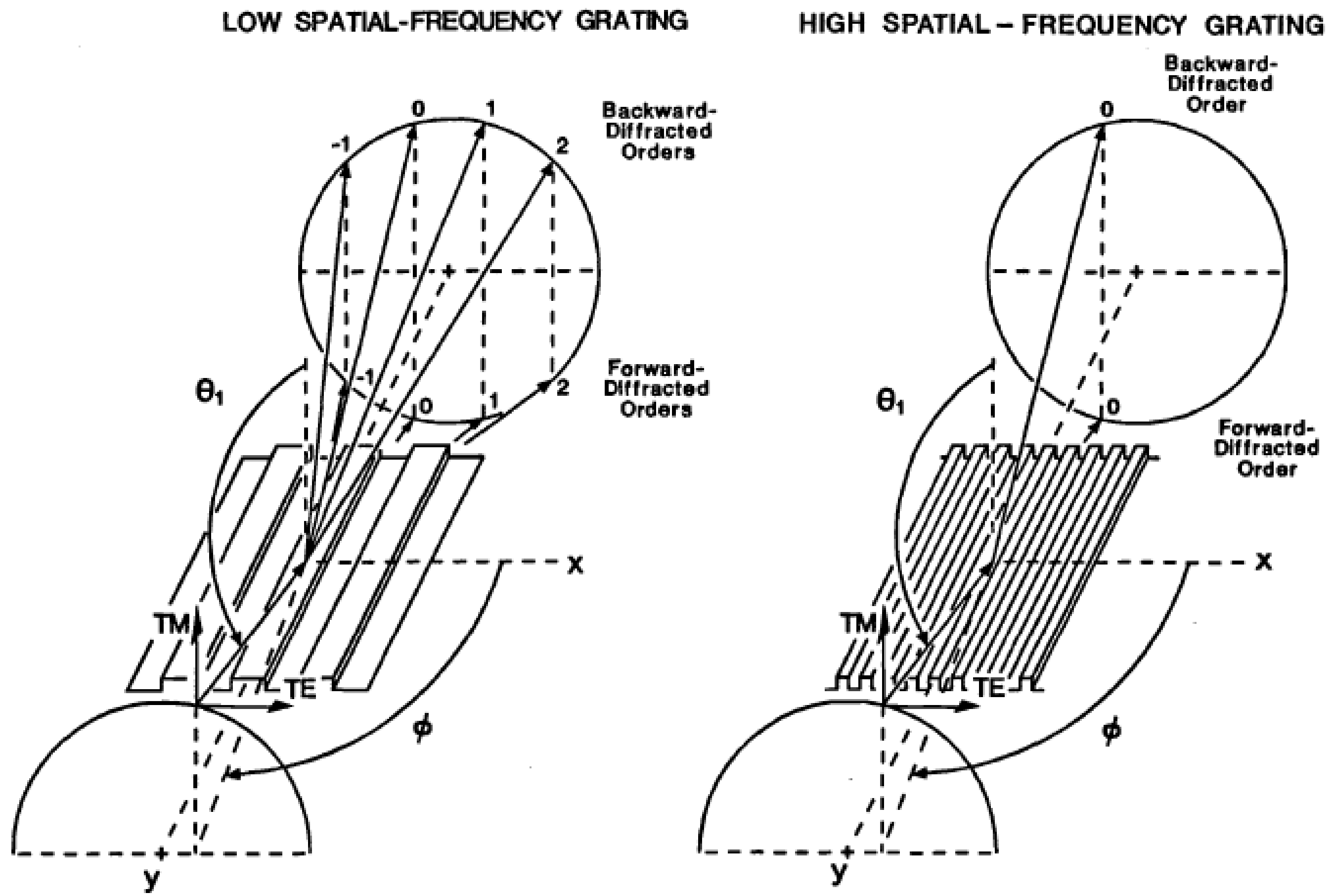


Rigorous Coupled Wave Analysis (RCWA)
Holographic Grating Scanner Example
3D-Diffraction Problem (Conical Diffraction)



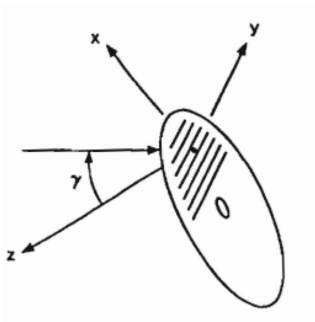


Conical Diffraction for Low- and High-Spatial Frequency Gratings



Rigorous Coupled Wave Analysis (RCWA)
Holographic Grating Scanner Example

3D-Diffraction Problem (Conical Diffraction)



Glass Substrate (n=1.5)

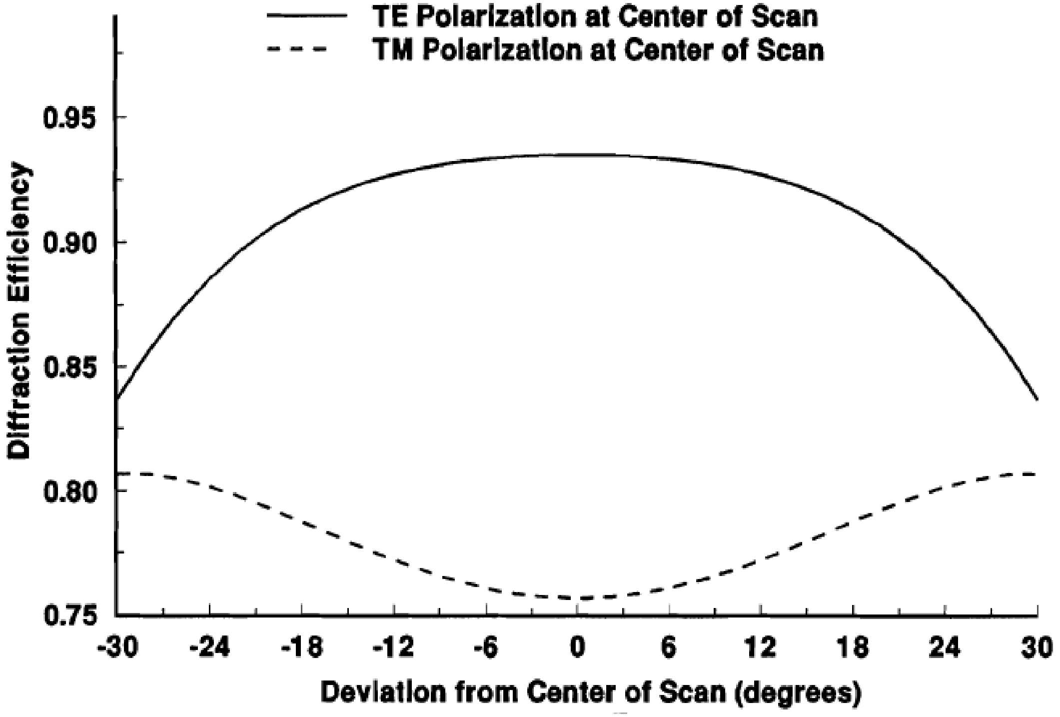
Angle of Incidence (γ) = 35deg

Freespace Wavelength = 1μm

Grating Period = 0.87μm

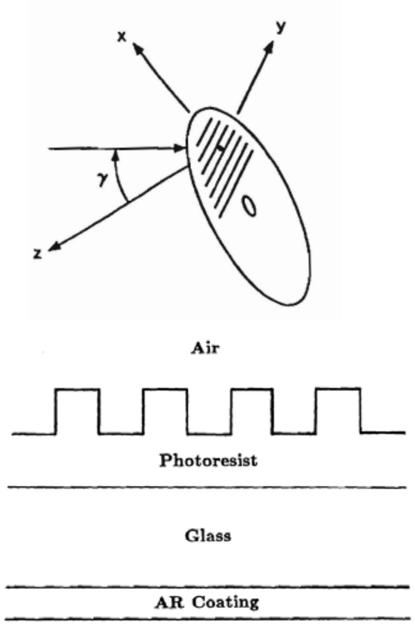
Filling Factor = 0.50

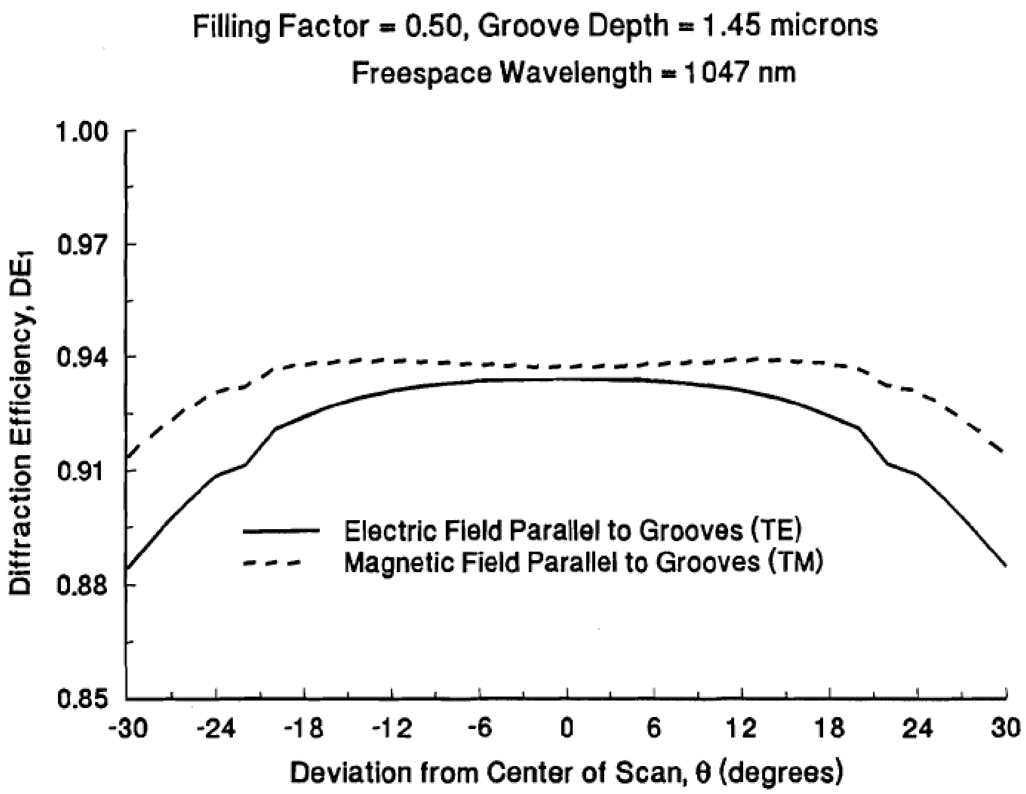
Groove Depth = 1.5μm



Rigorous Coupled Wave Analysis (RCWA)
Holographic Grating Scanner Example

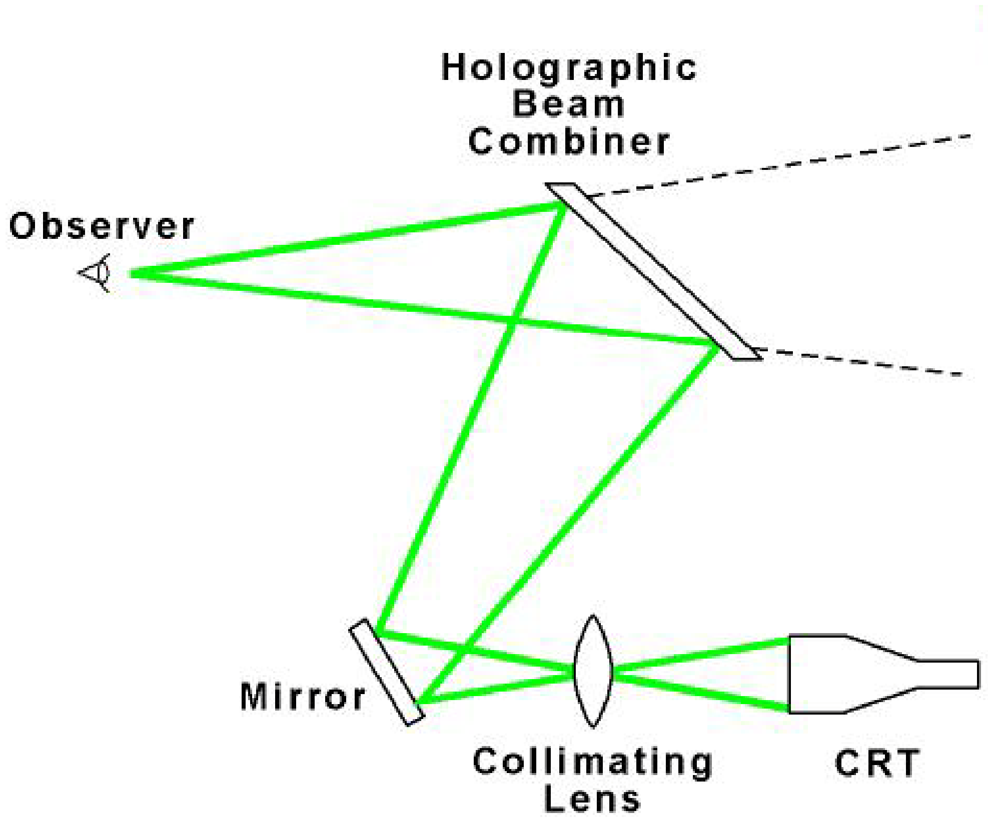
3D-Diffraction Problem (Conical Diffraction)



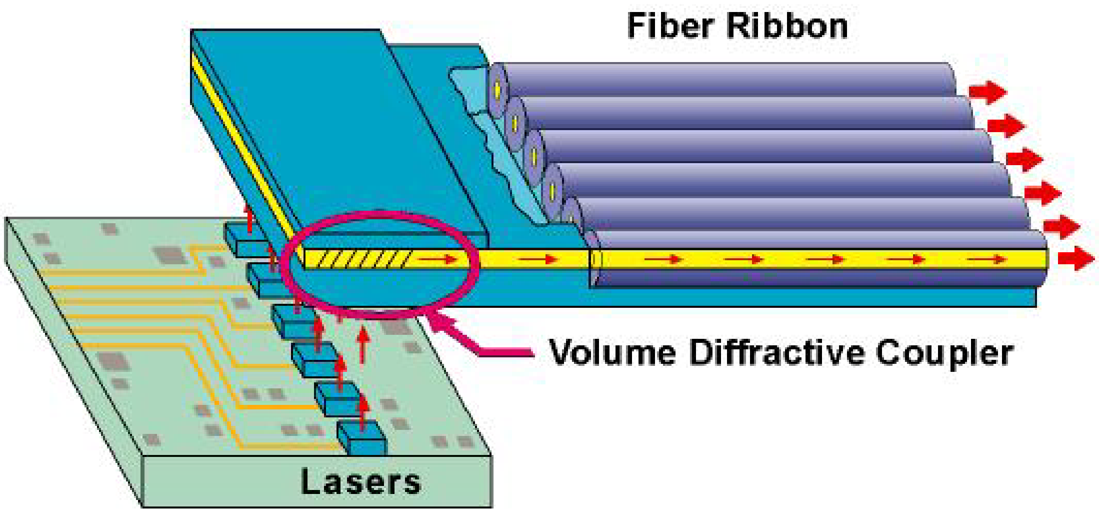


Glass Substrate (n=1.531)
Angle of Incidence (γ) = 33 deg
Freespace Wavelength = 1.047μm
Photoresist Grating
Photoresist Thickness = 2.4μm
Grating Period = 0.96μm
Filling Factor = 0.50
Groove Depth = 1.45μm

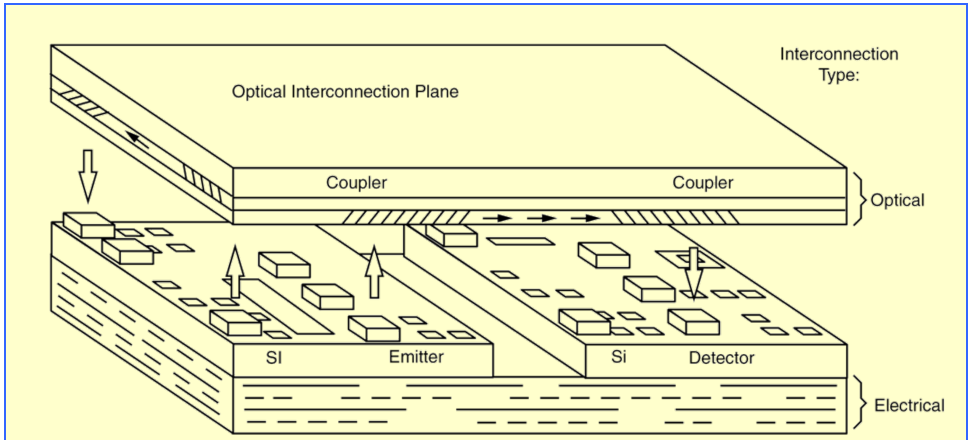
HOLOGRAPHIC HEAD-UP DISPLAYS



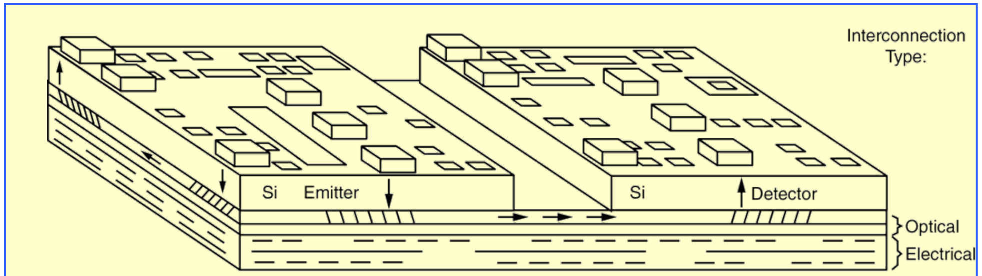
OPTICAL INTERCONNECTION



Optical Interconnect Architectures

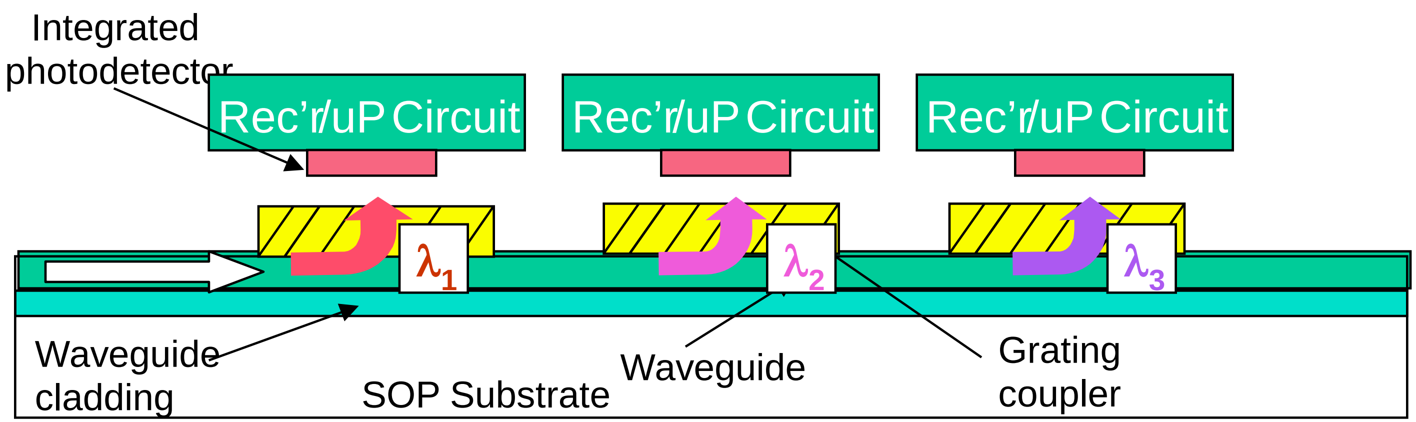


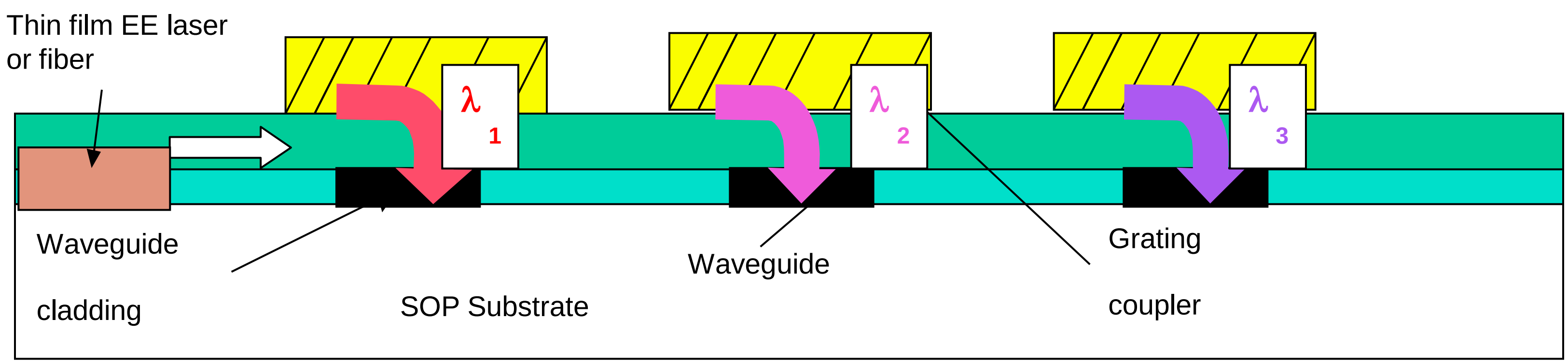
Intra-Chip and Inter-Chip Interconnections Through Optical Plane



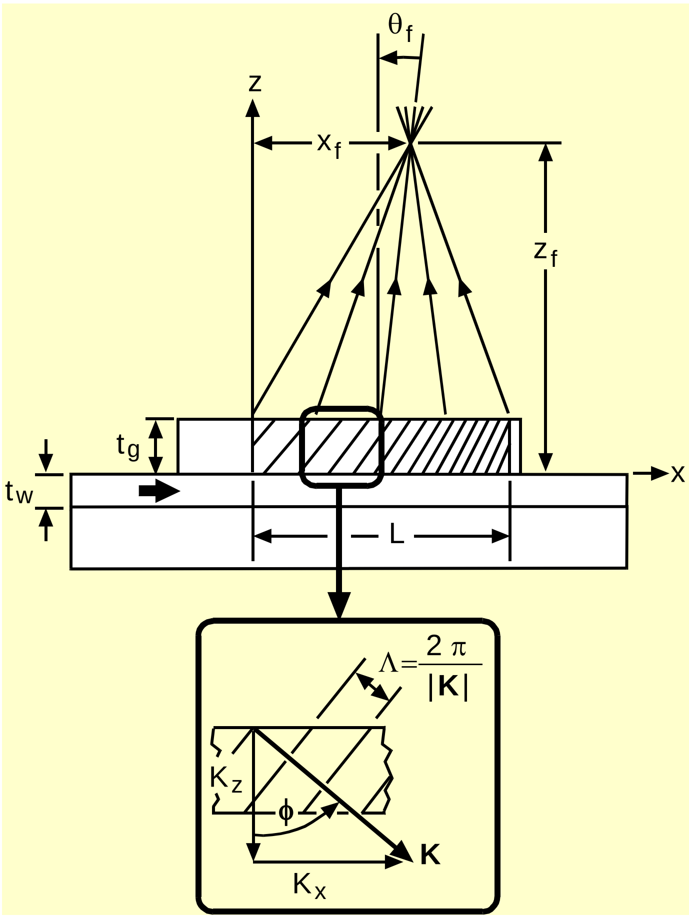
Intra-Chip and Inter-Chip Interconnections Through Substrate

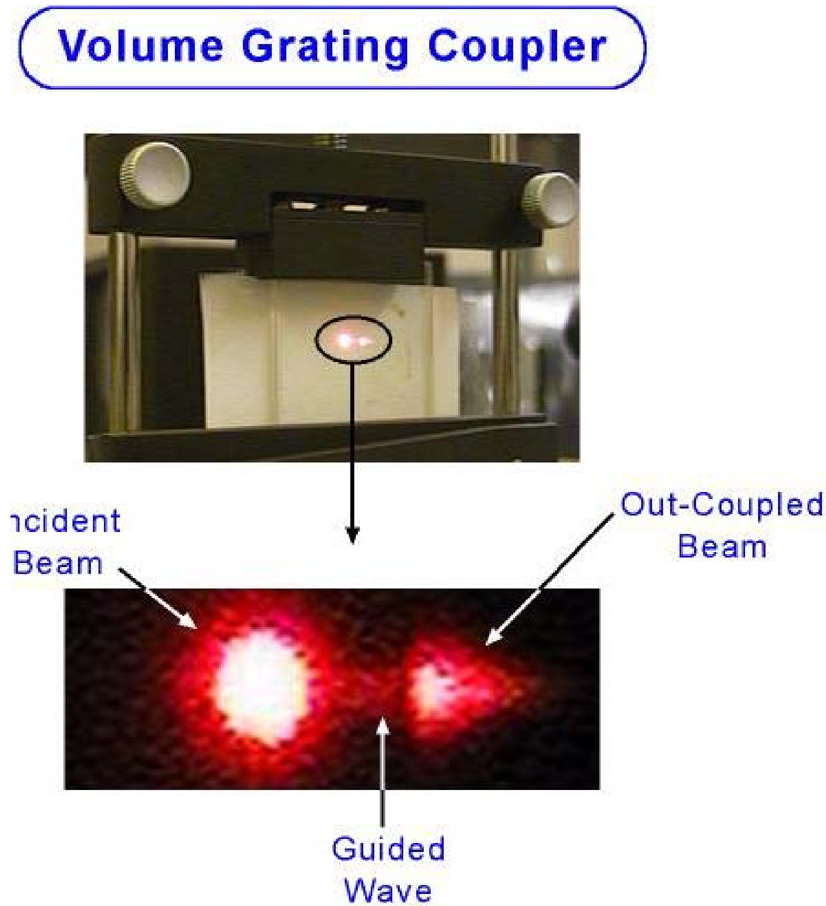
OPTOELECTRONICS PACKAGING
WAVELENGTH DIVISION DEMULTIPLEXING



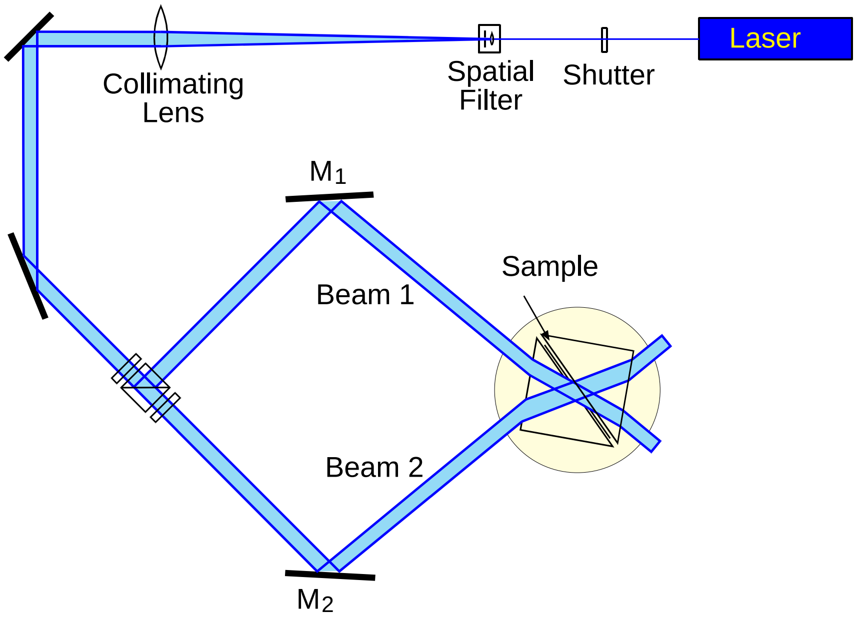


Holographic Grating Coupler

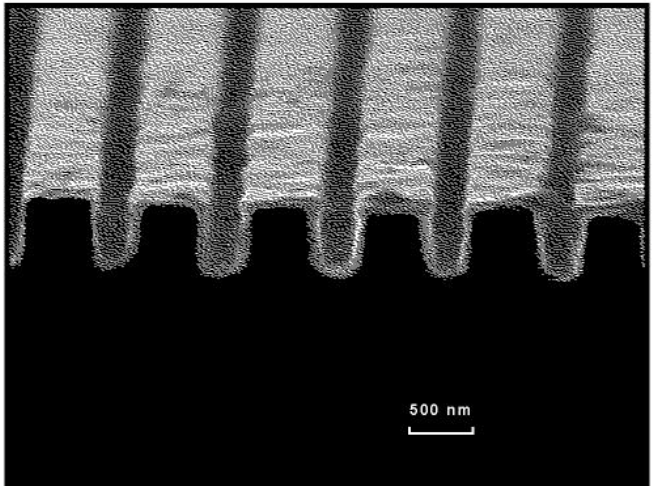




INTERFEROMETRIC GRATING FABRICATION FACILITY

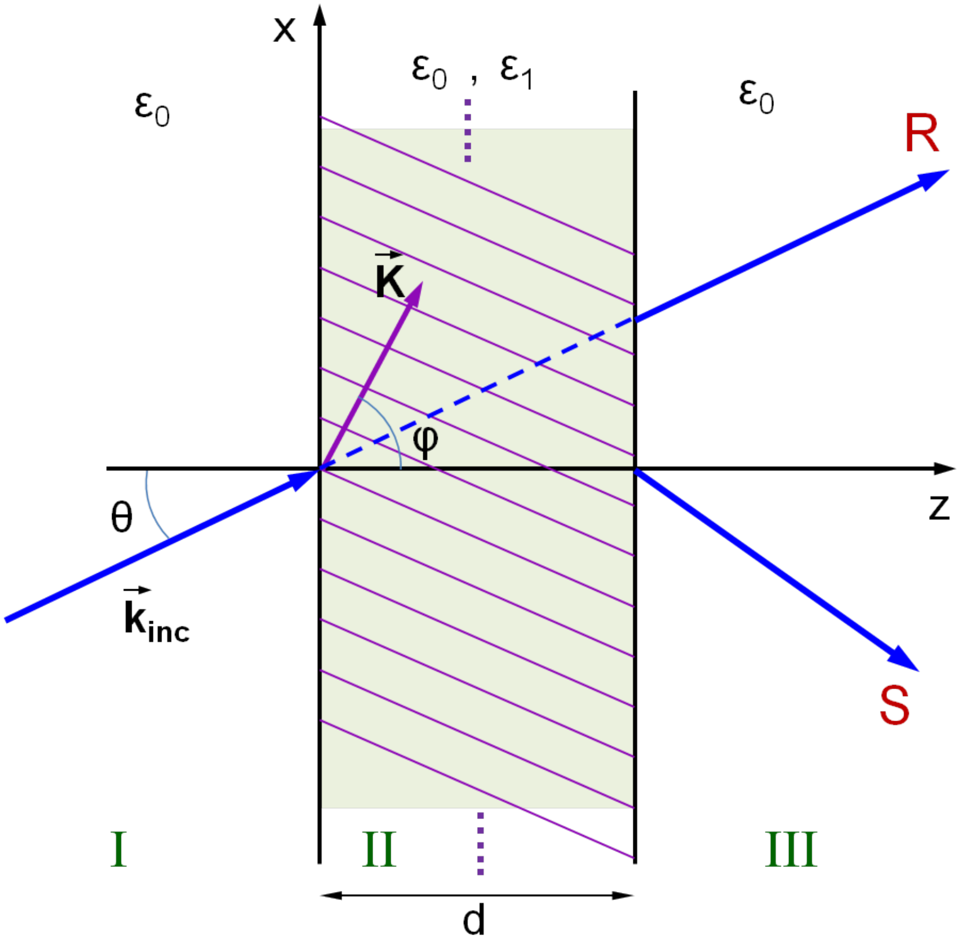


823 nm PERIOD GRATING



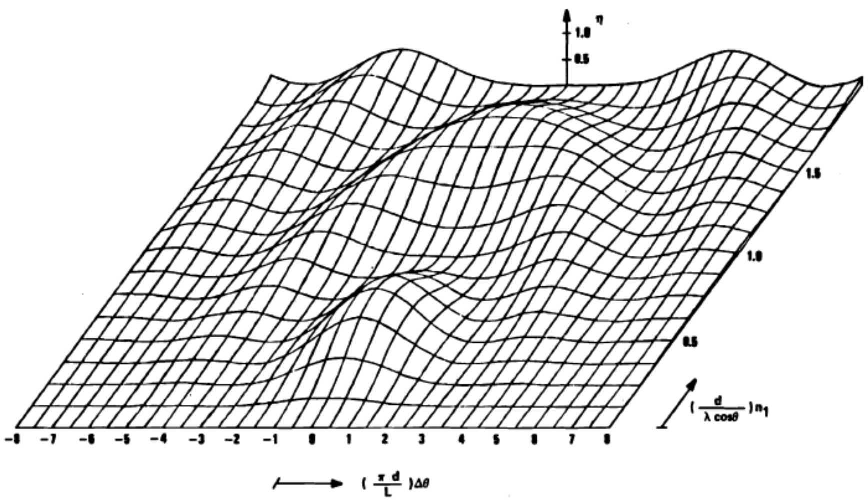
Kogelnik's Two-wave Coupled-wave Theory

(Transmission Grating Case)

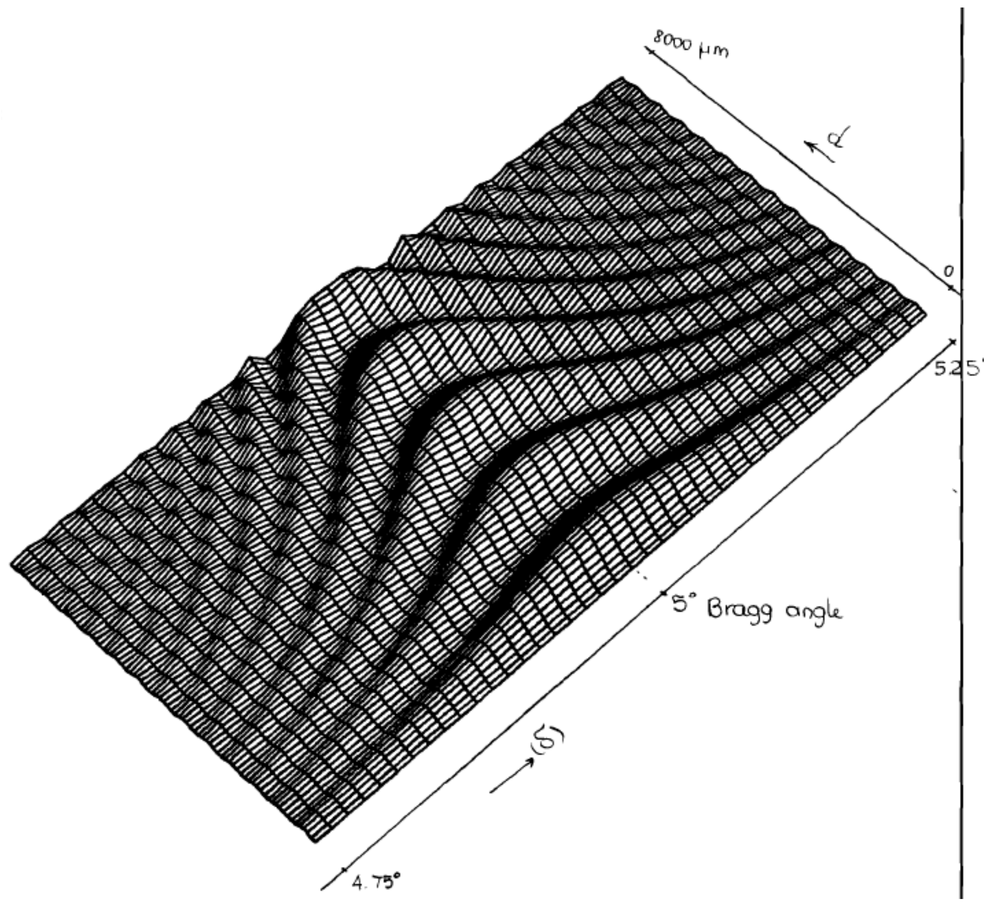


$$
\begin{aligned}
DE &= \frac{\sin^2\left[(\gamma^2+\xi^2)^{1/2}\right]}{1+(\xi/\gamma)^2}, \\
\gamma &= \frac{\pi n_1 d}{\lambda_0 (c_R c_S)^{1/2}}, \\
\xi &= \frac{\vartheta d}{2 c_S}, \\
\vartheta &= \frac{k_0^2 n_0^2 - |\vec{\sigma}|^2}{2 k_0 n_0}, \\
k_0 &= \frac{2\pi}{\lambda_0}, \qquad n_0 = \sqrt{\varepsilon_0}, \qquad n_1 = \frac{\varepsilon_1}{2 n_0}, \\
c_R &= \cos\theta, \qquad c_S = \cos\theta - \frac{K}{k_0 n_0}\cos\phi, \\
\vec{K} &= \frac{2\pi}{\Lambda}\left[\hat{z}\cos\phi + \hat{x}\sin\phi\right], \\
\vec{k}_{inc} &= k_0 n_0 \left[\hat{z}\cos\theta + \hat{x}\sin\theta\right], \\
\vec{\sigma} &= \vec{k}_{inc} - \vec{K},
\end{aligned}
$$

Angular Sensitivity of "Thick" Gratings



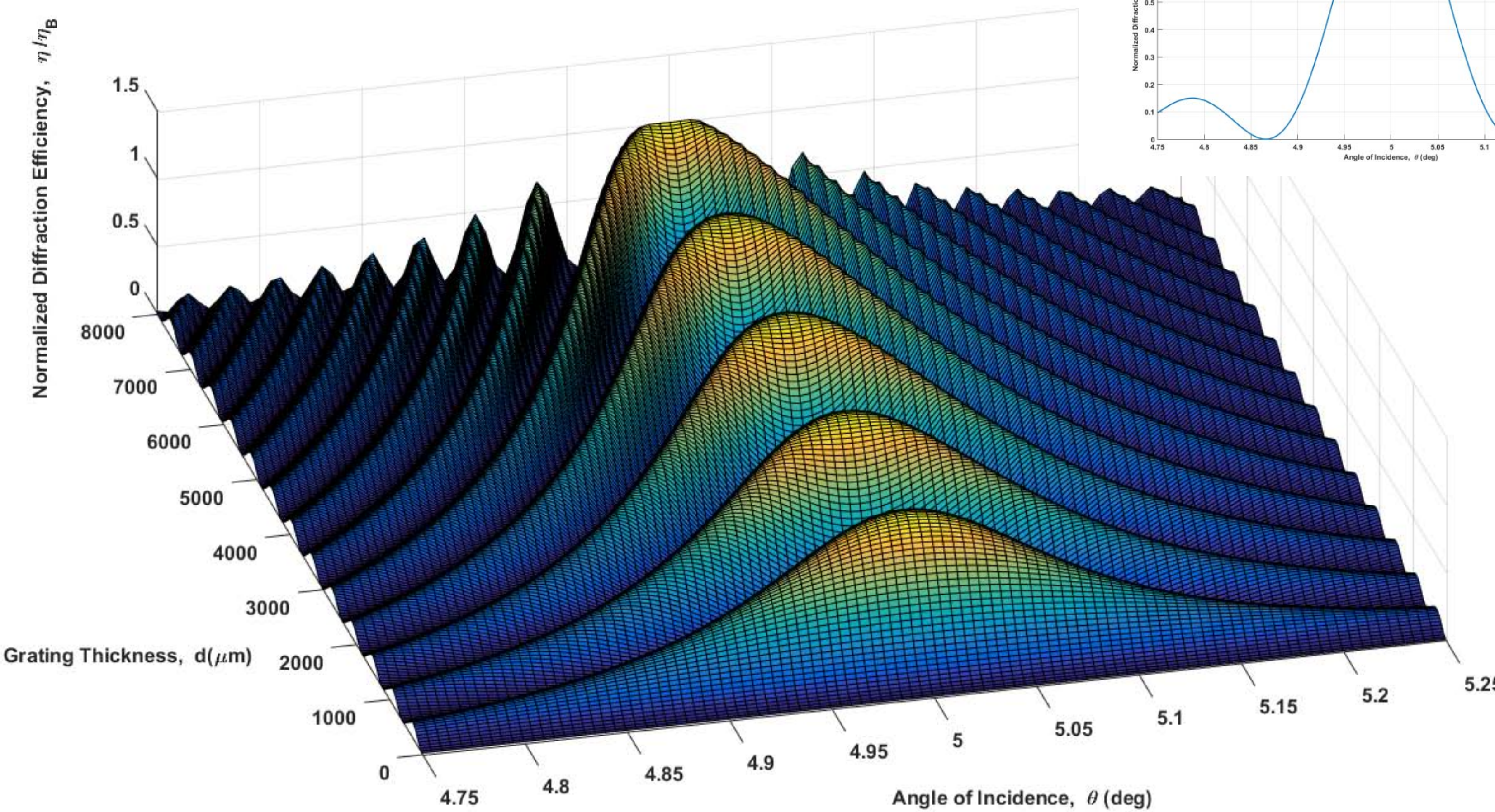
DIFFRACTION EFFICIENCY (η) AS A FUNCTION OF REFRACTIVE–INDEX MODULATION AMPLITUDE (n_1) AND ANGULAR DEVIATION (Δθ) FROM THE BRAGG ANGLE AS MEASURED INSIDE THE MEDIUM

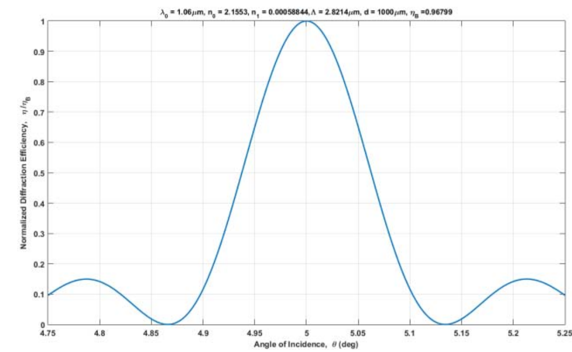


Angular Sensitivity of "Thick" Gratings

Case Parameters (Transmission Grating)

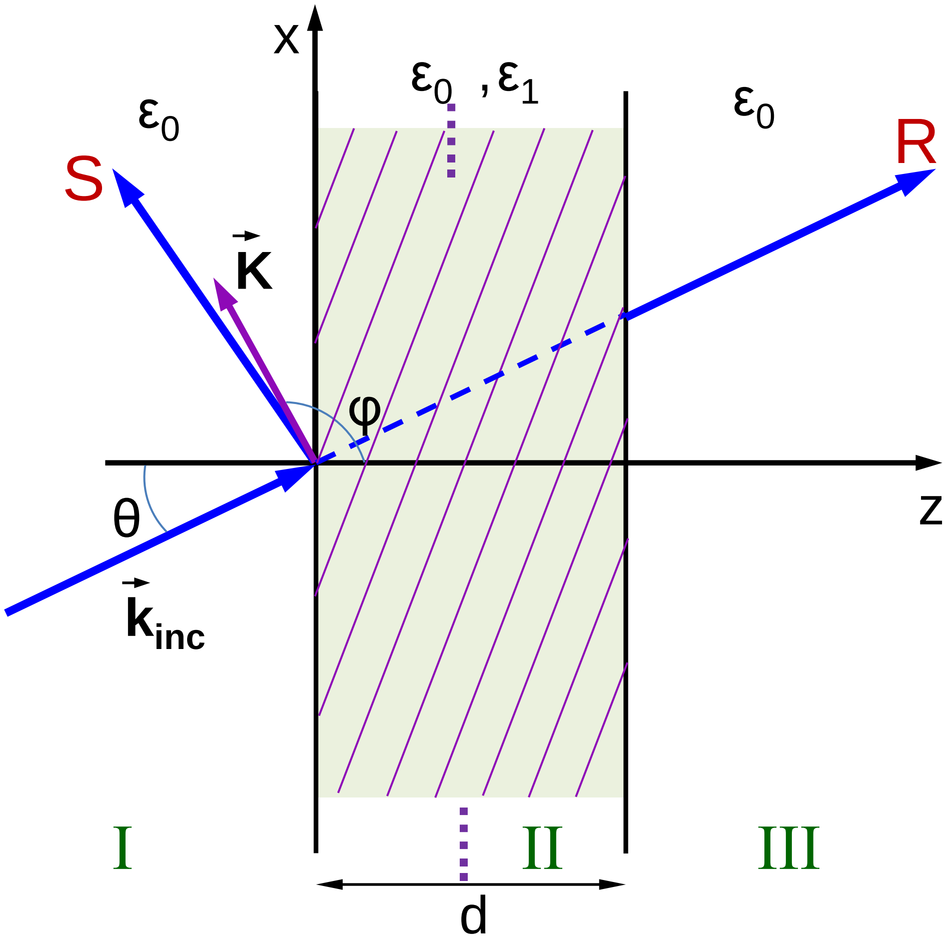
λ_0 = 1.06μm, n_0 = 2.155313, n_1=0.588444×10^{-3}, Λ = 2.821431514μm, ϕ =90°





KOGELNIK's TWO-WAVE COUPLED-WAVE THEORY

(Reflection Grating Case)



$$DE = \frac{1}{1+\dfrac{1-(\xi/\gamma)^2}{\sinh^2\left[(\gamma^2-\xi^2)^{1/2}\right]}},$$

$$\gamma = \frac{\pi n_1 d}{\lambda_0(|c_R c_S|)^{1/2}},$$

$$\xi = -\frac{\vartheta d}{2c_S},$$

$$\vartheta = \frac{k_0^2 n_0^2 - |\vec{\sigma}|^2}{2k_0 n_0},$$

$$k_0 = \frac{2\pi}{\lambda_0}, \qquad n_0 = \sqrt{\varepsilon_0}, \qquad n_1 = \frac{\varepsilon_1}{2n_0},$$

$$c_R = \cos\theta, \qquad c_S = \cos\theta - \frac{K}{k_0 n_0}\cos\phi,$$

$$\vec{K} = \frac{2\pi}{\Lambda}\left[\hat{z}\cos\phi + \hat{x}\sin\phi\right],$$

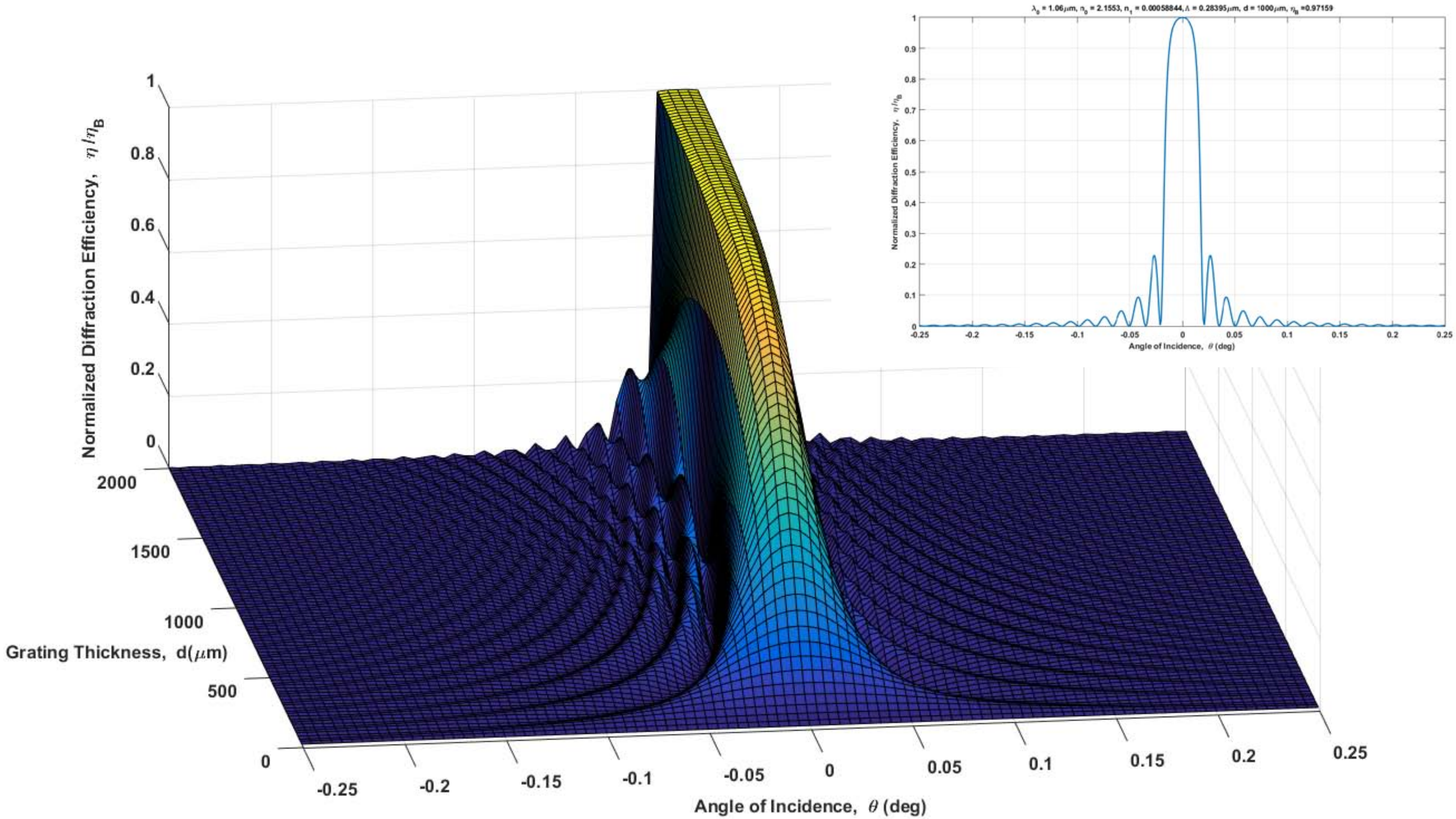
$$\vec{k}_{inc} = k_0 n_0\left[\hat{z}\cos\theta + \hat{x}\sin\theta\right],$$

$$\vec{\sigma} = \vec{k}_{inc} - \vec{K},$$

Angular Sensitivity of "Thick" Gratings

Case Parameters (Reflection Grating)

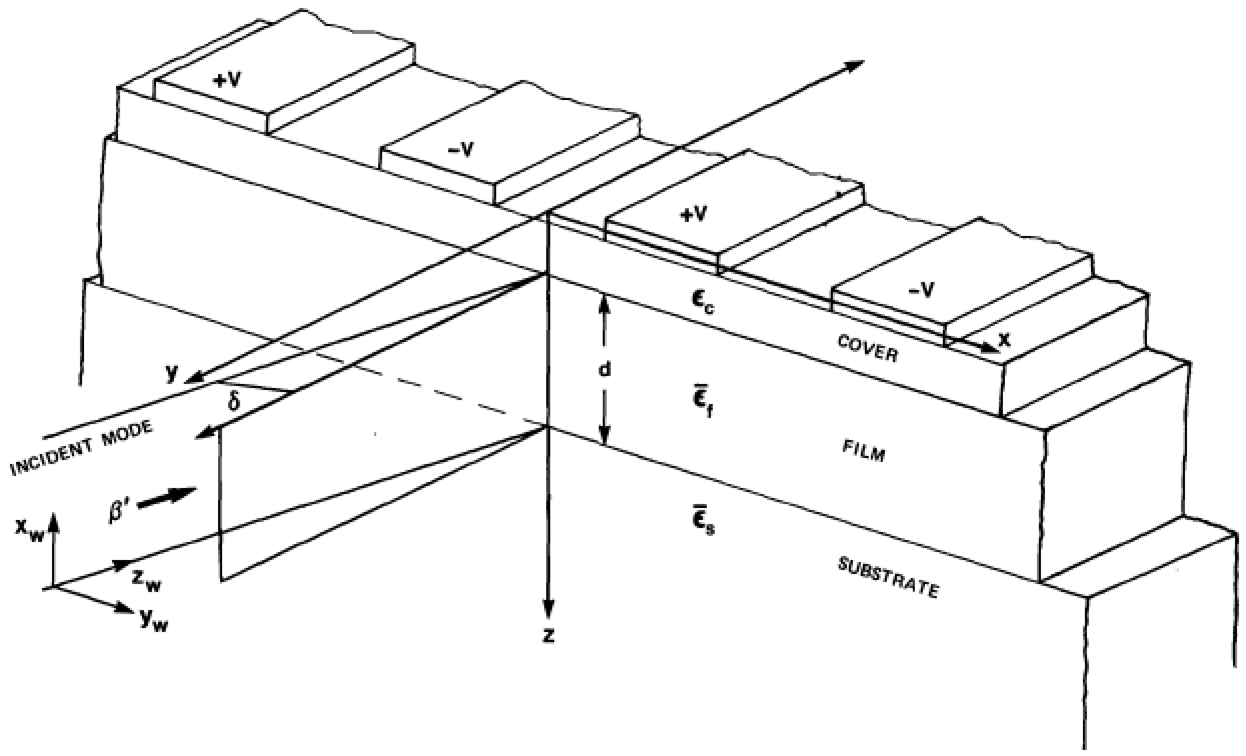
λ_0 = 1.06μm, n_0 = 2.155313, n_1=0.588444×10^{-3}, Λ = 0. 283945434μm, ϕ = 150°



Angular Sensitivity of "Thick" Gratings

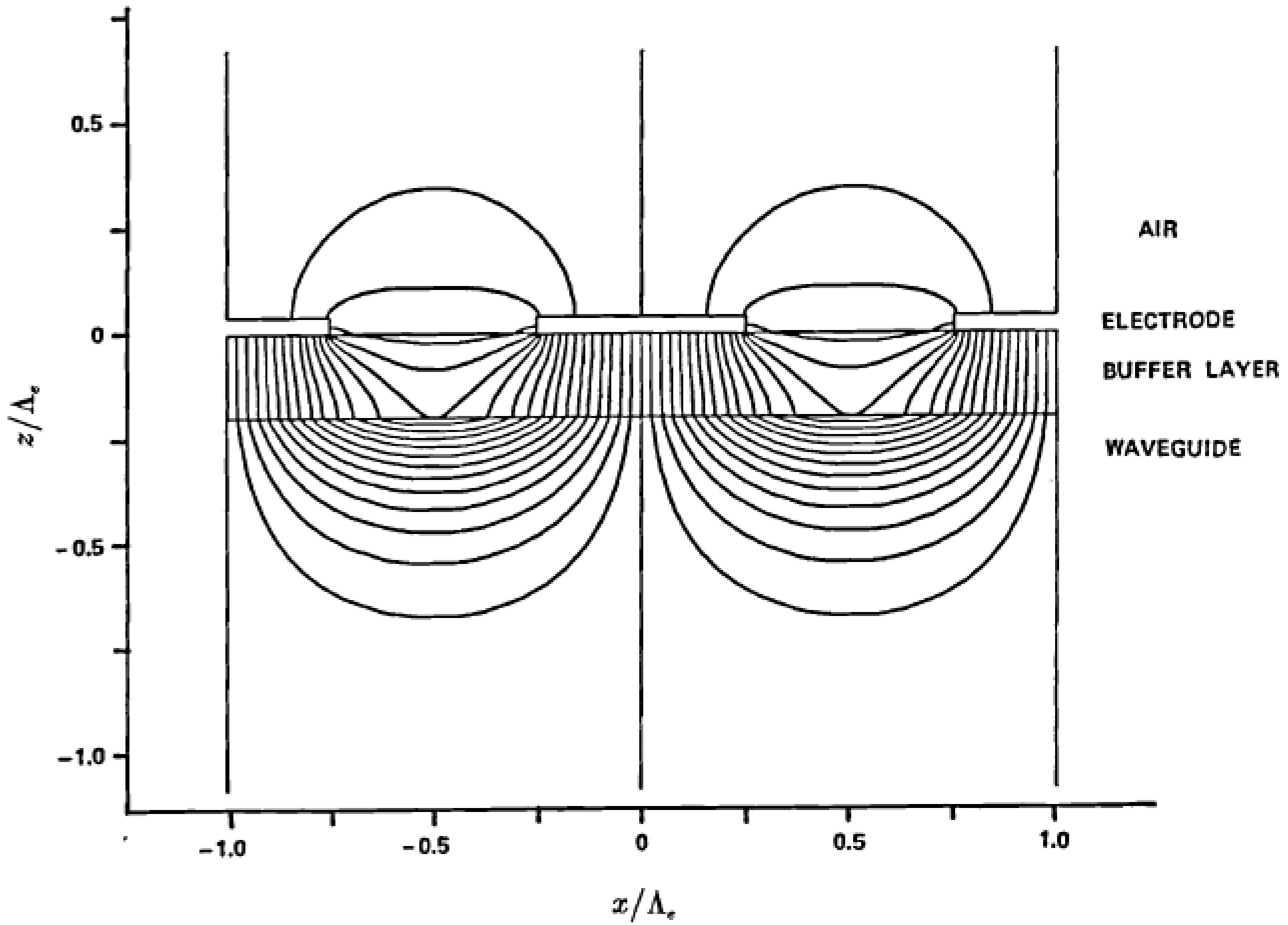
η_B	η/η_B	$A = 2\xi/\pi$
→ 0	0.99	0.1105
"	0.98	0.1566
"	0.95	0.2491
"	0.90	0.3561
"	0.80 (1dB)	0.5694
"	0.70	0.6467
"	0.60	0.7678
"	0.50 (3dB)	0.8859
0.5	0.99	0.1082
"	0.98	0.1532
"	0.95	0.2438
"	0.90	0.3484
"	0.80 (1dB)	0.5039
"	0.70	0.6326
"	0.60	0.7509
"	0.50 (3dB)	0.8660
1.0	0.99	0.1002
"	0.98	0.1420
"	0.95	0.2258
"	0.90	0.3226
"	0.80 (1dB)	0.4662
"	0.70	0.5848
"	0.60	0.6933
"	0.50 (3dB)	0.7987

Interdigitated Electrodes Electro-optic Grating

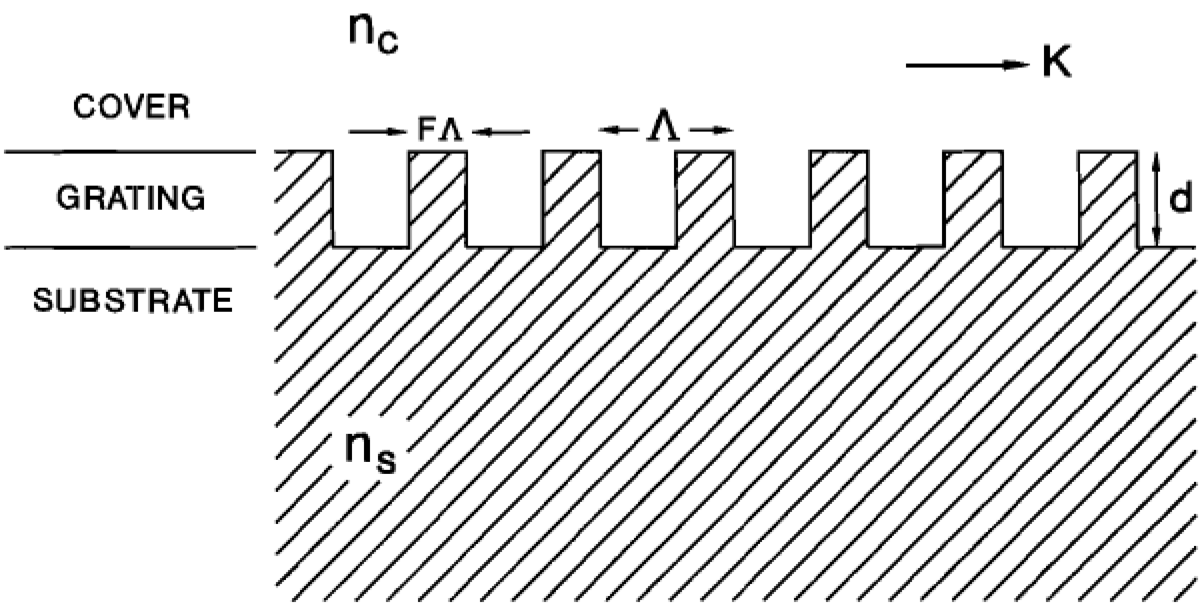


Interdigitated Electrodes Electro-optic Grating

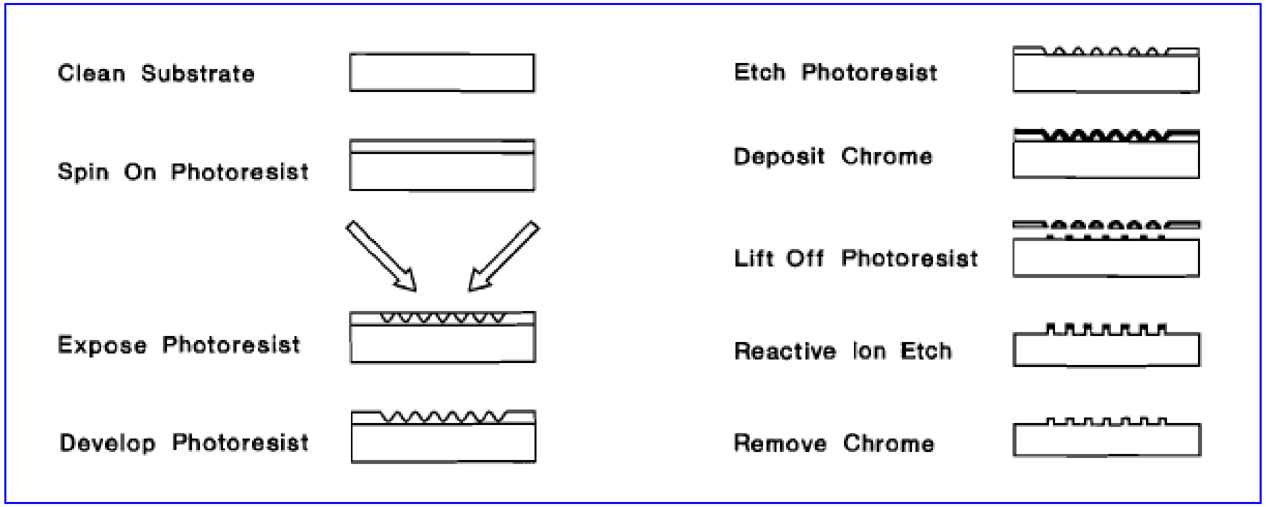
D-Field Lines

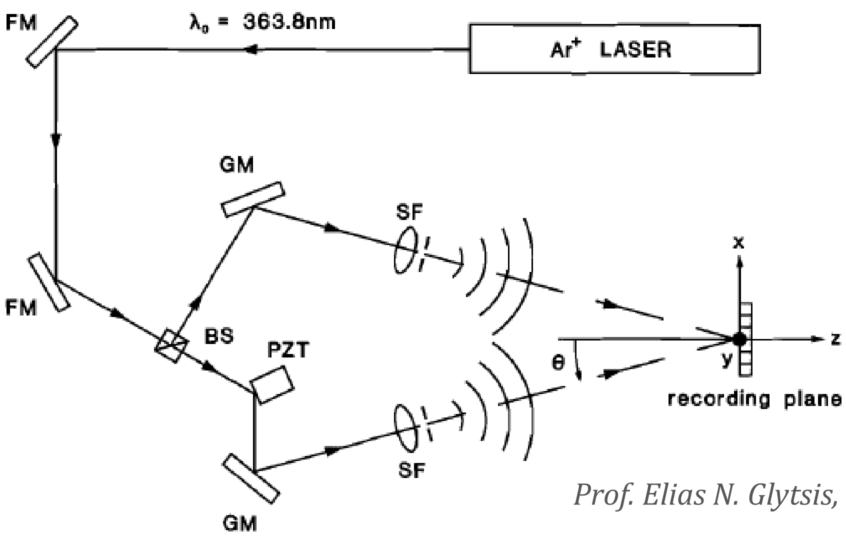


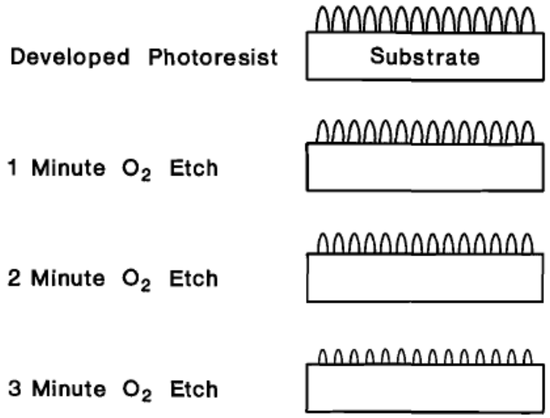
Rigorous Coupled Wave Analysis (RCWA)
Antireflecting Surface-Relief Grating Example
Rectangular-Groove Grating



Rigorous Coupled Wave Analysis (RCWA)
Antireflecting Surface-Relief Grating Example
Rectangular-Groove Grating Fabrication Process

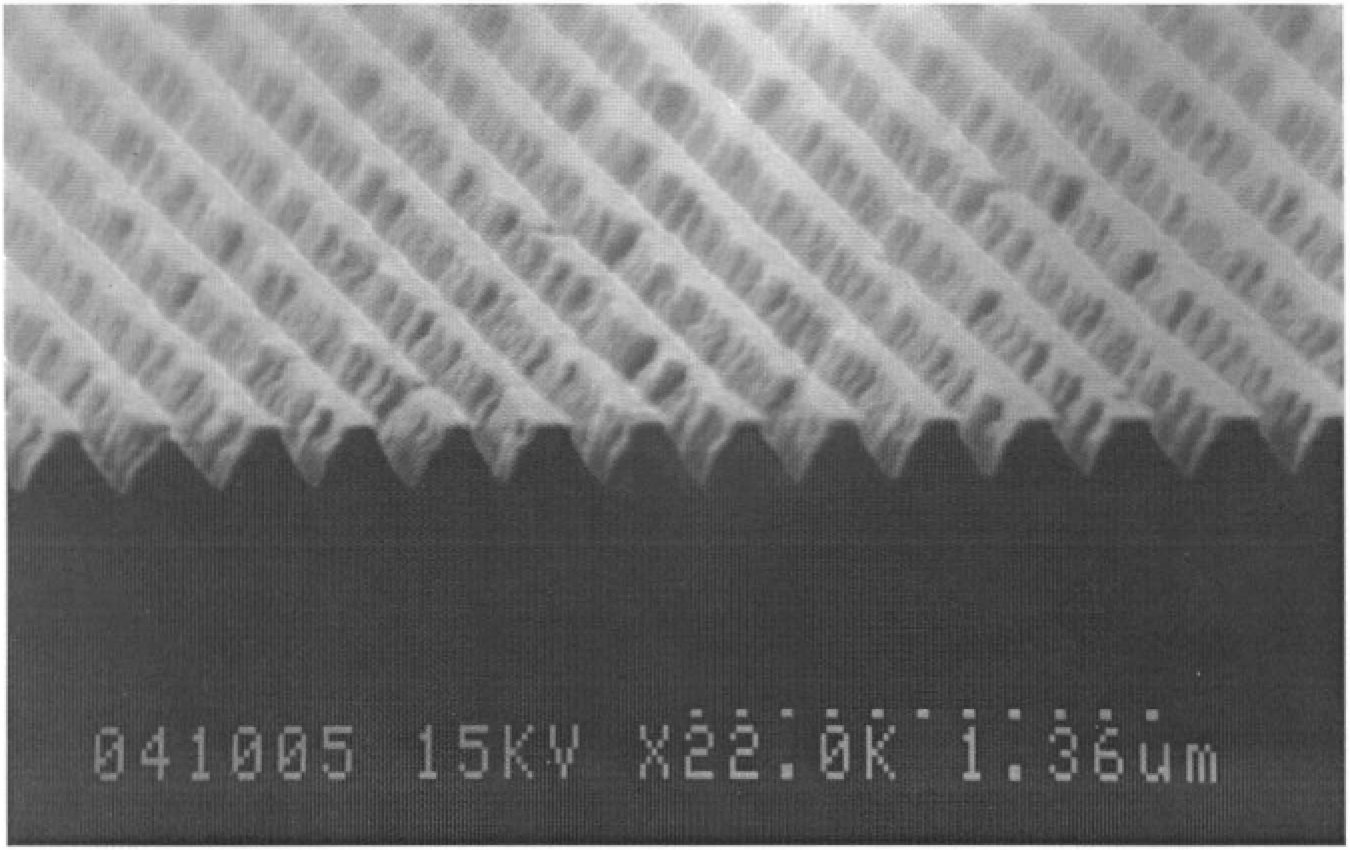






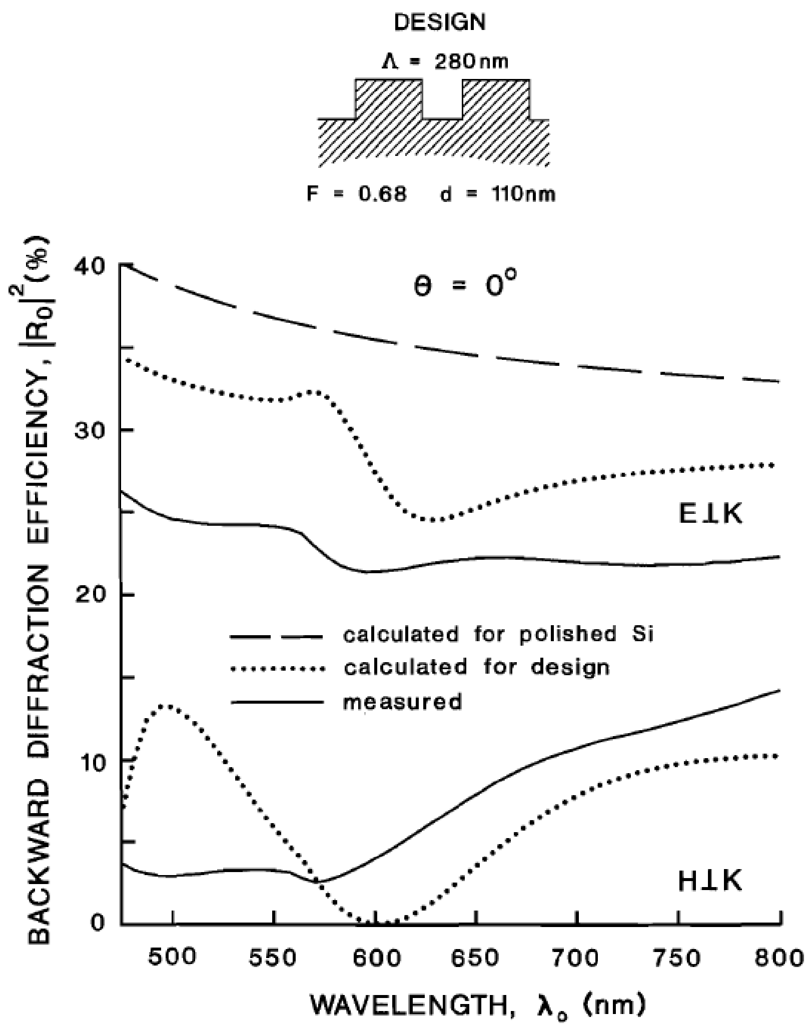
Rigorous Coupled Wave Analysis (RCWA)
Antireflecting Surface-Relief Grating Example

Electron-Microscope Picture of Fabricated Grating

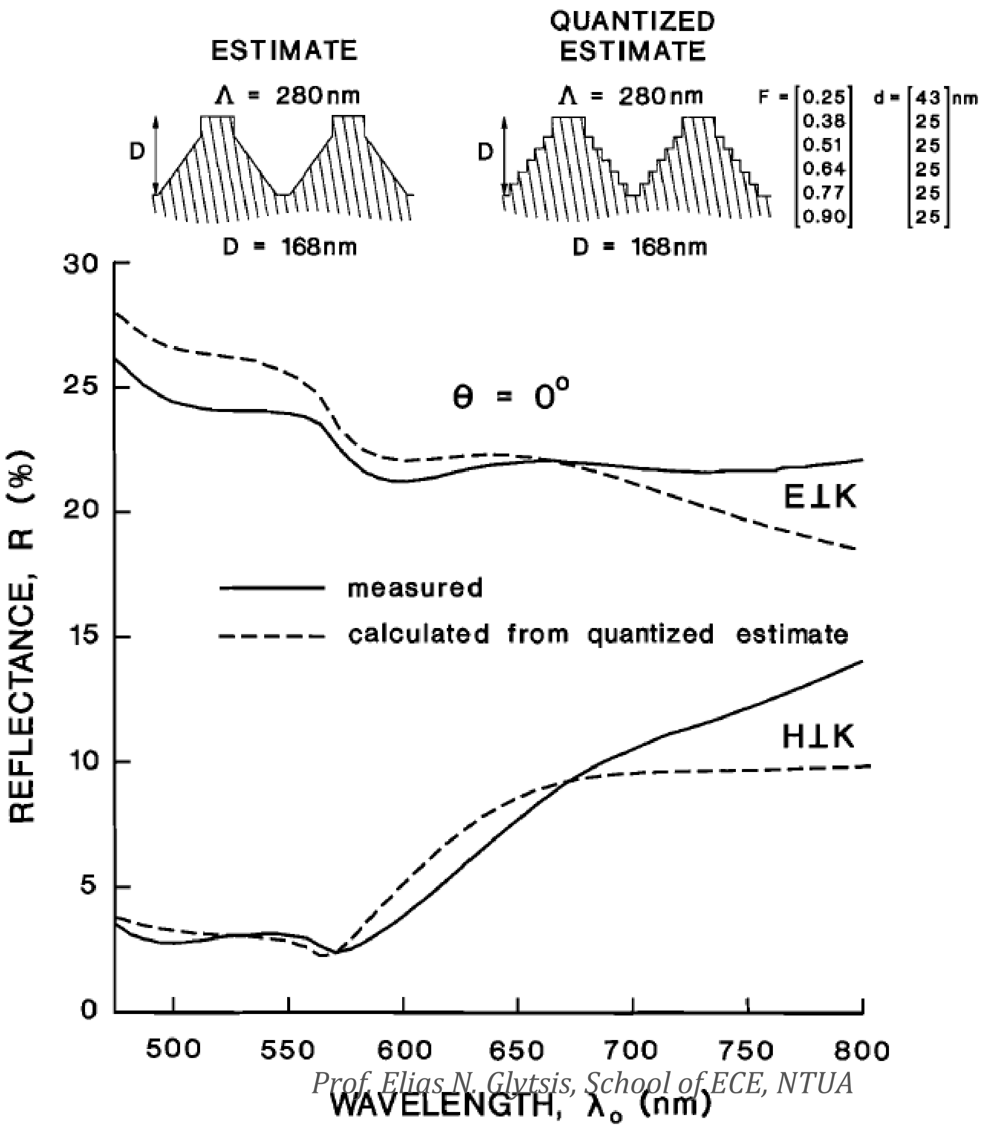


Rigorous Coupled Wave Analysis (RCWA)
Antireflecting Surface-Relief Grating Example

Spectral Response of Grating



Rigorous Coupled Wave Analysis (RCWA)
Antireflecting Surface-Relief Grating Example
Spectral Response of Grating



Rigorous Coupled Wave Analysis (RCWA)
Antireflecting Surface-Relief Grating Example

Spectral Response of Grating